UNIVERSITY OF ALBERTA

THE EFFECTS OF EXCHANGEABLE CATIONS ON SOME PROPERTIES

OF CLAY SHALES

A THESIS

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by

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ABSTRACT

This thesis presents the effects of adsorbed cations on some phys-ical properties of a Northern Alberta clay shale. Through chemical treatment and the medium of cation exchange, this soil was altered to produce modified soils whose dominant cations were sodium, potassium, magnesium, calcium (all of which were present to varying degrees in the natural soil), and hydro-gen. The natural soil was classified by tests including specific gravity, grain size analyses, Atterberg limits, determination of exchangeable cations and cation exchange capacity, and X-ray diffraction. The modified soils and natural soils were tested by standard procedures to determine the type and amount of exchangeable cations, Atterberg limits, permeability, and consol-idation characteristics.

The sodium modified soil had the highest liquid limit; highest plasticity index; most moisture difference between the liquid and shrinkage limits; lowest permeability, being seven times as impermeable as the natural soil; and exhibited two to three times as much swelling as the other soils. The potassium modified soil had the highest plastic limit; lowest plasticity index; least moisture difference between the liquid and shrinkage limits; and the highest permeability, being more than twice as permeable as the natural soil. The calcium, magnesium, and hydrogen modified soils had plasticity, shrinkage, and swelling characteristics similar to the natural soils but were one and half times to two times more permeable.

The effects of the cations on the permeability, swelling, and shrinkage of a given soil can be predicted in general terms from the results of Atterberg limit tests on homionic variations of the soil.

ACKNOWLEDGEMENTS

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GLOSSARY OF TERMS

Adsorption: The concentration of material at the contact zone (interface) of two substances. Usually applies to the molecular or ionic state of division; for example, potassium ions concentrated on the surface of soil colloids.

Anion: An ion carrying a negative charge of a electricity.

Cation: An ion carrying a positive charge of electricity.

Cation-Exchange Capacity: The sum total of exchangeable cations adsorbed by a soil at pH 7, expressed in milliequivalents per 100 gms of dry soil.

Cation Exchange: The replacement in a colloidal system of positively charged ions (cations) by other cations.

C axis: Crystals are referenced by means of three mutually perpendicular axes. The C axis is perpendicular to the major dimensions of the crystal.

Crystal: A microscopic sample of a solid substance exhibiting some degree of geometrical regularity or symmetry.

Divalent Cation: An ion with a deficiency of two electrons.

Exchangeable Cations: Cations adsorbed on the soil particles which are capable of being replaced by cations in solution.

Homionic Soil: A soil in which all the exchangeable cations adsorbed on the colloids are of one kind.

Ion: An atom or mdecularly-bound group of atoms which has gained or lost one or more electrons and which thus has a negative or positive electric charge.

Leaching: Removal of materials in solution.

Milliequivalent: The total cation exchange capacity of a soil is expressed
by milliequivalents (m. e.) of ions 100 gms of soil will adsorb.
The term milliequivalent is used because equal weights of the
various exchangeable cations are not equal in terms of chemical
reaction. The equivalent is defined as equal to one gram of
hydrogen, and the milliequivalent as 1/1000 th of an equivalent.
Therefore a milliequivalent of H = 0.001 gm. A milliequivalent
of calcium $= \dfrac{1}{1000} \times \dfrac{40.08}{2} = .02$ gm.

Mineral: A naturally occurring combination of inorganic elements and
ions in the form of salts or other compounds either in
crystalline or amorphous condition.

pH: A notation to designate or indicate the degree of acidity or alkalinity
of systems. Technically, the common logarithm of the
reciprocal of the hydrogen ion concentration (grams per litre)
of a system.

Trivalent Cation: An ion with a deficiency of three electrons.

CHAPTER I

INTRODUCTION

1.1 Statement of the Problem

Soil is used extensively in civil engineering as a foundation material and as a construction material. Some soils are more suitable than others for these purposes. In the majority of cases, where an unsuitable soil is encountered, it is possible to replace the unsuitable soil or adapt the design to suit the conditions. In a few cases, the most notable being unstable slopes, it is generally impractical to remove the large volume of soil involved and it is often undesirable to move to another location. In these cases it is preferable to alter the engineering properties of the soil by mechanical, thermal, electrical, or chemical means in order to render it suitable.

Of the chemical methods, the improvement of the plasticity, permeability, and workability of the soil, using the medium of cation exchange*, has been under investigation for many years by soil physicists and physical chemists in the fields of agronomy and ceramics. However, research on the effect of cation exchange on other physical properties of soils - shrinkage, swelling, consolidation, and strength, of prime importance in the field of soil mechanics, was begun just over 20 years years ago. The scientific study of cation exchange in soils may make possible the development of superior means of stabilization and selection of the most appropriate stabilization method for use on individual projects

*Words marked with an asterisk are defined in the Glossary of Terms

and may dictate means by which the danger of failure of soil masses in service may be minimized.

The purpose of this investigation is to determine the effects of cation exchange on the engineering properties of a Northern Alberta clay shale.

1.2 The Phenomena of Ion Exchange and its Application to Soil Mechanics Problems.

It is now generally accepted by soil physicists and clay mineralogists that the physical properties of clays are governed by the nature of the clay crystals* and the water film surrounding the particle. The water film is dependent on the nature of the charges in the ion* atmosphere surrounding the particle. Replacement of an exchangeable ion may change the nature of the clay crystals as well as the character of the water film and consequently change certain properties of the clay.

By ion exchange is meant the reversible process by which cations* and anions* are exchanged between solid and liquid phases and between solid phases if in close contact with each other. In the heterogeneous soil system, the soil solution acts as the medium by which chemical reactions between members of the different phases and of the same phase are made possible even when the reactants are not in direct contact. These reactions are made feasible because of the property of the clay to adsorb* and exchange cations and anions. Considerable research has been carried out on the nature of cation exchange and the effect of changes in cations on the physical properties of soils. However, the phenomenon

of exchange of anions in the soils has received less attention. It has been established that such exchange does occur, though apparently to a far less extent than that of cations. Anions may replace the OH groups in clay minerals, and as these groups are much more plentiful in the kaolonite minerals than in other minerals, the kaolonite minerals are considered the seat of most anion exchange.

In the field of soil mechanics, the common objectives of altering soil physical properties by cation exchange are as follows:

(1) Increase the shearing strength.

(2) Reduce the amount of consolidation.

(3) Decrease the permeability to reduce seepage.

(4) Increase the permeability to reduce erosion.

(5) Reduce frost heave in fine textured soils.

Although laboratory results have demonstrated many useful effects of cation exchange, examples of successful application of this knowledge to the solution of significant engineering problems are few.

A classic example of the control of permeability of clay by means of cation exchange is the treatment of a lagoon lining on Treasure Island in San Francisco Bay by Lee (1941)[1]. Upon flooding of the lining with sea water sufficient to permit seepage through the lining of a total of 40 inches of depth, the ratio of exchangeable* sodium (Na+) ions to calcium (Ca++) ions was increased from 1:1 in the original soil to an average of 2:2:1: Excess salt water was then drained from the lagoon and fresh

    1. References are cited by indicating the author and the year of
       publication. The references are contained in the bibliography
       at the conclusion of the paper.
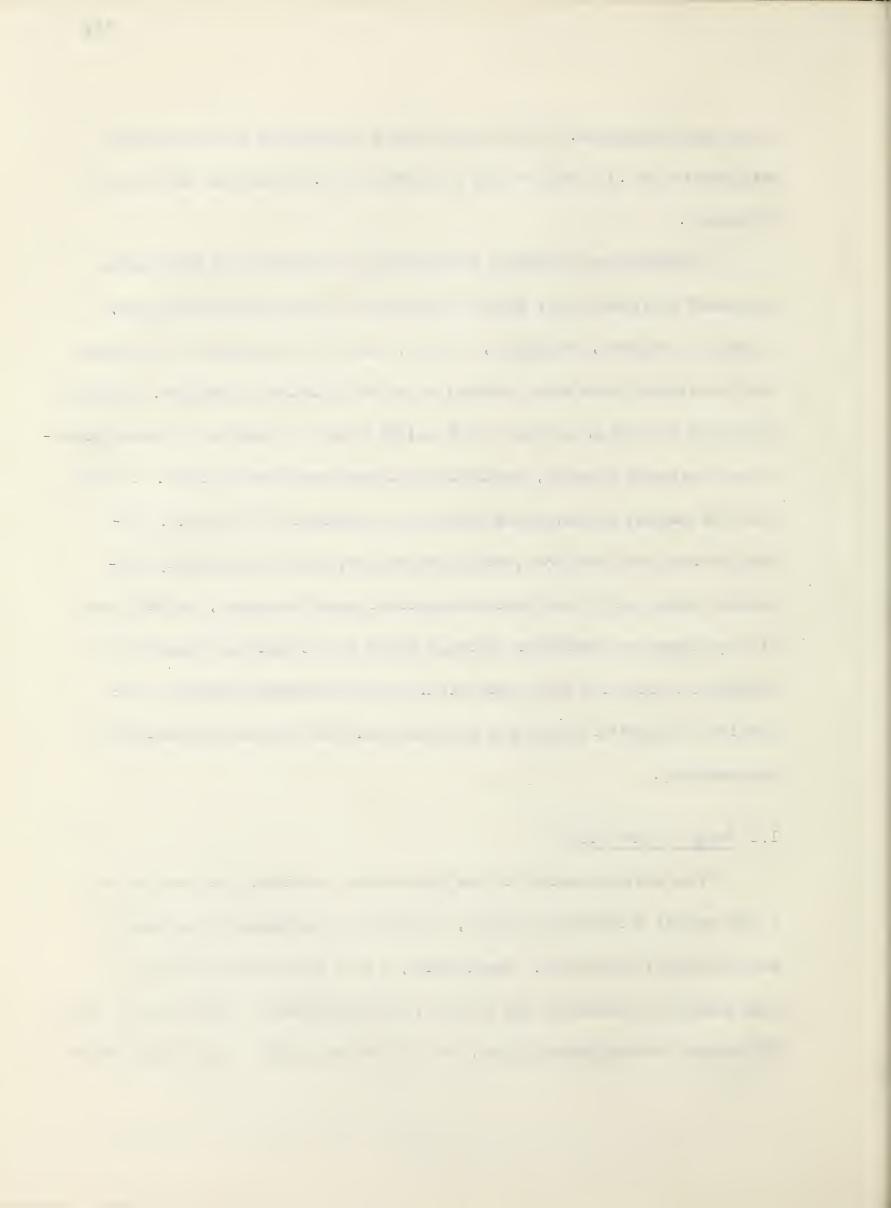
water was introduced. The seepage rate at completion of the operation was found to be .10 inch per day in contrast to 0.90 inch per day prior to treatment.

Stabilization of highway subgrades by introduction of divalent* or trivalent* inorganic ions, such as calcium in calcium hydroxide (lime) or salts of calcium, aluminum, or iron, has been investigated extensively but best results have been obtained so far with calcium hydroxide. Calcium hydroxide is used in amounts of 2% to 10% of the soil weight to reduce plasticity and increase strength, particularly in pavement base courses. In this case the natural exchangeable cations are exchanged for calcium. Although these methods have yielded satisfactory results in highway subgrades where only a few inches of material must be treated, stabilization of clay slopes or foundations of large works by mechanical admixture or hydraulic injection of chemicals has not proved feasible because of the quantity of material in place to be treated and the characteristically low permeability.

1.3 Scope of the Thesis

The work presented in this thesis was conceived to determine on a soil typical of Northern Alberta, the effect of exchangeable cations on some physical properties. Specifically, a well defined natural clay of high plasticity containing 65% calcium, 21% magnesium, 7% potassium, and 7% sodium exchangeable cations, was altered by means of controlled cation

exchange to produce modified sodium, potassium, magnesium, calcium, and hydrogen saturated clays. The modified clays, along with the natural clay, were subjected to Atterberg limit tests and consolidation tests on both undisturbed and remoulded specimens to determine the effect of the type of adsorbed cation on the plasticity, shrinkage, swelling, permeability, and consolidation characteristics of this soil.

The experimental data is interpreted in the light of existing theories and compared with the results of previous investigations on soils containing similar clay minerals. Where definite trends are established, the practical engineering uses of the observed phenomena are suggested.

CHAPTER 2

THE CATION EXCHANGE MATERIAL

2.1 The Chemical and Mineralogical Nature of Clays

Cation exchange is a property of the clay material of soils -
the active substance is hydrated aluminosilicate. Cation exchange is a
property not peculiar to the colloidal state but to certain kinds of surfaces.
In 1930 it was discovered by Hendricks and Fry that the fine-grained inorganic
material of soils is crystalline. This discovery led to the identification of
the specific substances that are responsible for cation exchange in soil.
The clay minerals are not simply fragments of minerals which were in
the parent material. They are compounds developed by chemical and phys-
ical change produced by weathering of the parent material. The parent
material is the mineral in igneous and metamorphic rock. Clay minerals
are found in both the unconsolidated form and in sedimentary rock (clay
shales).
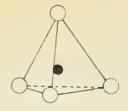
Clay minerals are generally plate shape and are characterized
by a layer lattice structure. The layers are composed of planes of silicon
(Si^{++++}) ions in which each Si ion is situated at the center of a tetrahedron
formed by four oxygen (O^{--}) ions as shown in fig. 1(a), and planes of
aluminum (Al^{+++}), iron (Fe^{++} or Fe^{+++}), or magnesium (Mg^{++}) ions sur-
rounded by six oxygen (O^{--}) or hydroxyl (OH^{--}) ions arranged in the form
of an octahedron as shown in fig. 1(b). Marshal, cited by Baver (1958),
divides clays and related minerals into four groups:

Tetrahedron	Octahedron
● Silicon O Oxygen	● Aluminum, magnesium etc. O Oxygen
Fig. 1 (a)	Fig. 1 (b)
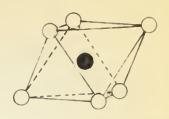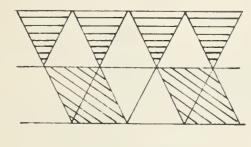
Kaolin Group	Hydrated Mica Group
Tetrahedron layer / Octahedron layer	Tetrahedron layer / Octahedron layer / Tetrahedron layer
Fig. 1 (c)	Fig. 1 (d)
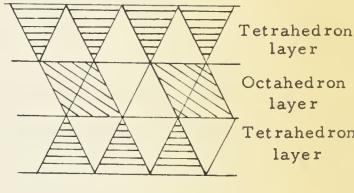
Montmorillonite Group	Chlorite Mineral
Tetrahedron layer / Octahedron layer / Tetrahedron layer / Water	Hydrated Mica layer / Brucite layer
Fig. 1 (e)	Fig. 1 (f)
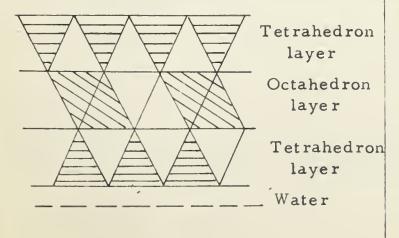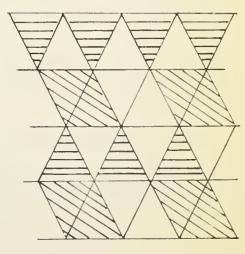
(1) Kaolin group with a 1:1 lattice type.

(2) Hydrated mica group with a 2:1 lattice type.

(3) Montmorillonite or expanding lattice group with a 2:1 lattice type.

(4) Fibrous clay group.

According to Grim (1953) there is another important group, which he classifies as the regular mixed-layer group. The chlorite mineral belongs to this group.

2.2 Kaolin Group

The chief characteristic of the kaolin group is the 1:1 lattice structure, that is, a lattice in which silica tetrahedron layers alternate with aluminum octahedron layers as shown in fig. 1(c). Members of this group are kaolonite, dickite, nacrite, hydrated halloysite, metahalloysite, and others. The sheets are very compact so that there is no room for ions or small molecules between them. Therefore the physical properties are determined by external forces only. The charges of the lattice are balanced internally so that the crystal is unable to attract external cations except by the negative charges of terminal 0 ions on the lattice edges. These forces are small in number per unit weight, but probably numerous enough to account for the low cation exchange capacity* of the kaolin group. The members of the group exhibit only slight hydration and adsorptive properties.

2.3 Hydrated Mica Group

This group is characterized by a 2:1 lattice type which consists

of one layer of aluminum octahedrons sandwiched between two layers of aluminum tetrahedrons as shown in fig. 1(d). The tetrahedrons carry negative charges due to the substitution of Al+++ for Si++++ in the center of the tetrahedrons. There are two subgroups:

(1) Illite:

Charges on the tetrahedron layer are satisfied by potassium (K+) ions which are embedded partially within the layers, acting as cementation agents. As the potassium decreases, the hydration increases. When completely dehydrated, the resulting clay mineral is called muscovite.

(2) Vermiculites:

Charges on the tetrahedron layers are balanced by positive charges in the octahedron layers. Water molecules are found between the layers.

The cation exchange capacity of this group is intermediate between that of the kaolin group and the montmorillonite group. Exchangeable cations probably lie relatively near the terminal edges of the plates and possibly in considerable part on the exposed planar surfaces of extremely thin crystals as adjacent lattice layers appear to be firmly held together.

2.4 Montmorillonite or Expanding Lattice Group

This group also has a 2:1 (2 Si tetrahedrons and 1 Al octa - hedron) lattice type but in this case the lattices expand and contract according

to the amount of water present as shown in fig. 1(e). This type of accordion

like structure would indicate a large internal surface area. Cations and

water are adsorbed not only on the outer surfaces but also on the internal

surfaces within the crystal so that this group has high cation exchange cap-

acity. Most of the exchangeable cations are found between the sheets.

Members of this group are:

Montmorillonite - Some Al in the octahedron layers
replaced by Fe or Mg.

Beidellite - Some Si in the tetrahedron layers replaced

by Al.

Nontronite - Al in the octahedron layers replaced

by Fe.

Saponite - Some Si in the tetrahedron layers replaced

by Al
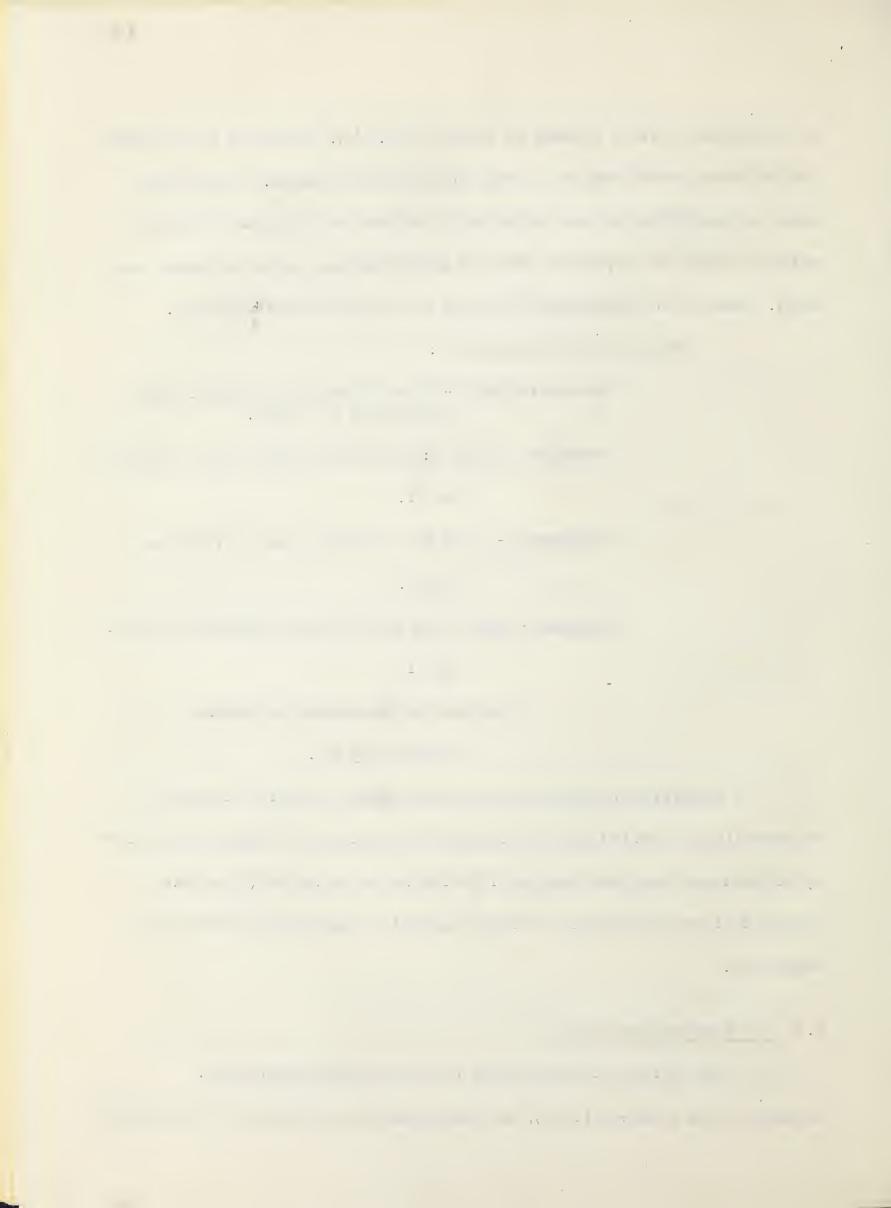
- Some Al in the octahedron layers

replaced by Mg.

Kelley(1948) suggests that the high cation exchange property of

montmorillonite and beidellite is largely due to negative charges occasioned

by deficiency of positive charges in the layers of the lattice (Mg^{++} has

replaced Al^{+++} in the montmorillonite and Al^{+++} has replaced Si^{++++} in

beidellite).

2.5 The Fibrous Clay Group

The fibrous clay group has not been studied extensively.

Bradley, cited by Baver (1958), has investigated the structure of attapulgite

one of the fibrous clay group, and has found that the silicon atoms occur in strips arranged alternately on either side of the oxygen atoms.

2.6 The Regular Mixed-Layer Group

Mixed layer minerals are those in which there is interstratification of the layer clay minerals in which the individual layers are of the order of a single or a few aluminosilicate sheets. Mixed layer structures are as stable as those composed of a single kind of layer. A regular mixed-layer mineral is one in which the stacking along the C axis* is a regular repetition of the different layers. An example of this group is the chlorite mineral which is composed of a regular alternative of hydrated mica and brucite layers as shown in fig. 1(f).

2.7 Variations Within the Lattice

While analysis of the Hydrated Mica and Montmorillonite minerals has shown that the lattice units of clay minerals are well ordered, it does not follow that the chemical composition of all the lattice units, even in a given particle, are uniform. In fact calculation on the basis of mass analysis shows that a variable percentage of the lattice units are charged while the remainder are electrically neutral. The evidence is that variations in lattice composition among the cell units of a given particle and especially between the units of particles from different sources is an outstanding characteristic of these two groups of clay minerals.

2.8 The Shape of Clay Particles

In order to visualize the causes of plasticity, a knowledge of the shape of clay particles is required. It is now well known that clay particles are not cubical or spherical in shape. This evidence is found in ultra-microscopic observations of clay, the double refraction of clay particles, the layering of particles during deposition, the nature of the clay crystals, and from electron-microscope micrographs. Research with the electron microscope has contributed much to the knowledge of the shape of clay minerals.

(1) Montmorillonite structure ranges from an amorphous appearing material to extremely thin plates.

(2) Beidellite particles are well defined and plate-like.

(3) Kaolonite particles are hexagonal plate shape with sharp, well defined edges.

(4) Halloysite particles, similar to Kaolonite in crystal structure, are well defined and rod-shaped.

The maximum thickness of a plate is determined by the dimension of a lattice unit in the direction of the C axis* but the length, breadth, and geometrical outline varies widely. The plate shape of the particles has much to do with the chemical and physical effects of clay minerals in the soil because a plate shape has a very large amount of surface area per unit of weight. Baver (1958) quoting from Ostwald points out the variation in surface area with the change in shape of 1 cc volume of material.

A sphere has a specific surface of 4.836 cm^2/cc, a cube has a specific surface of 6.0 cm^2/cc, and a disc of 1 micron (.001 mm) thickness has a specific surface of 2×10^4 cm^2/cc.
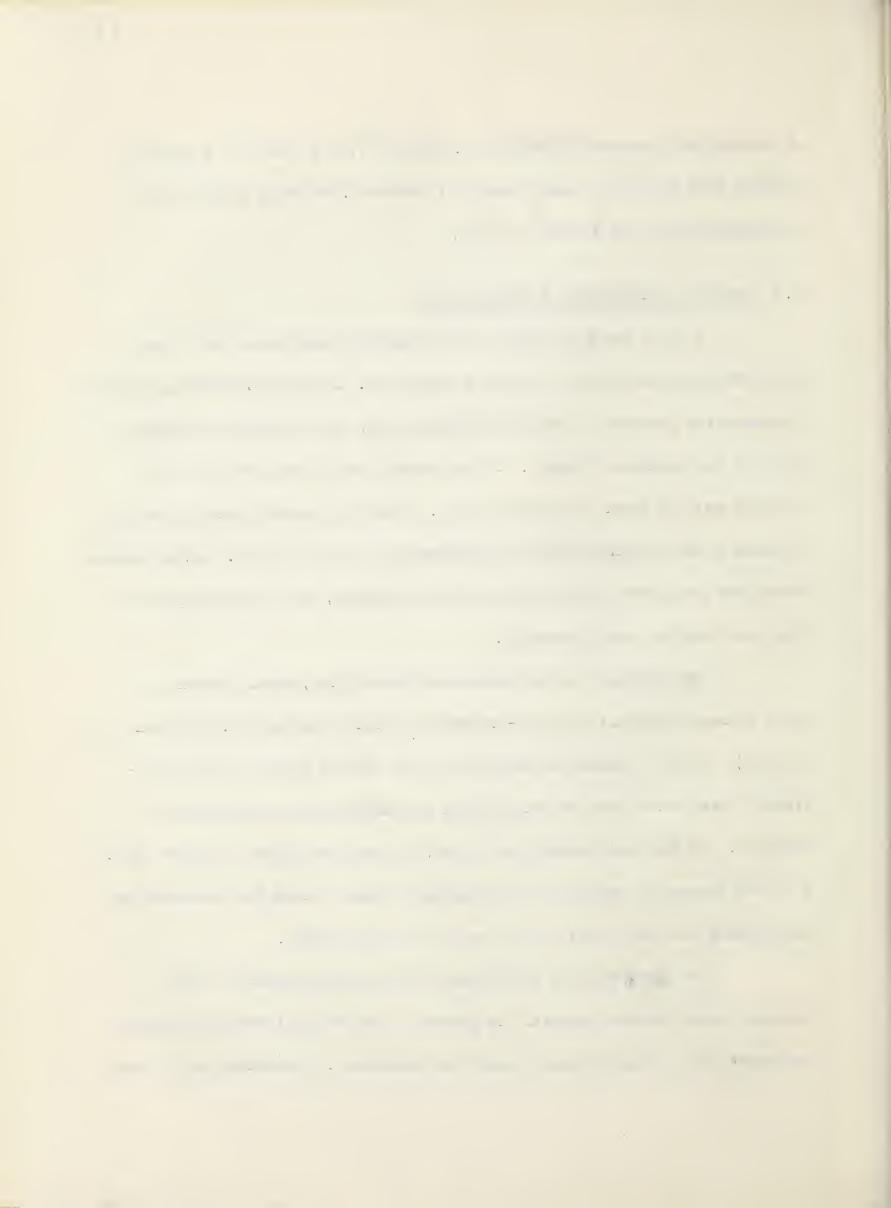
2.9 The Clay Minerals of Different Soils

Until a few years ago, soil scientists made no attempt to separate the different kinds of clay in a given soil. If the identification method indicated the presence of montmorillonite clay, the conclusion was that the soil was montmorillonitic. If the evidence was strong for kaolonite, the soil was put down as kaolonitic soil. However, about twenty years ago it began to be recognised that the problem was not so simple. Investigations since that time show that with very few exceptions, two or more types of clay are found in soils generally.

The evidence is that montmorillonitic clay, when present, is most concentrated in the finest-grained fraction of the soil (0.3 micron or less). This is consistent with the fact the lattice layers of montmorillonitic clay rarely exceed one micron in length and are usually much smaller. On the other hand, the crystals of kaolonite grow to larger size. For this reason the quantitative estimation of these clays is facilitated by subdividing the clay material into two or more fractions.

The geographical distribution of the various kinds of clay forms a very complex pattern. In general it can be said that the strongly leached* soils of humid areas tend to be kaolonitic. Grassland soils such

as those in the semi-arid areas of the Canadian Prairies, tend to be mont-morillonitic. Dryland soils are often found to contain much of the hydrated mica group of clay minerals. However there are sufficient exceptions to these general rules to make it necessary to say that the various clay mineral groups have been found in all types of climates in Europe and North America. Furthermore, clays below the current zone o f weather-ing will not have the same mineral composition as the surface layer if the climate during their deposition was different from the present climate.

By means of a private communication with the Alberta Soil Survey, Research Council of Alberta, the writer obtained the following information on the clay minerals of Alberta. There is considerable variety of parent materials from which the soils of Alberta were formed. However, since there has been much transporting and re-transporting of this mater-ial, there is basic uniformity throughout. Differences are in amount of constituents rather than kind. Montmorillonite and illite are the principal clay minerals.

2.10 Cation Exchange Capacity of the Common Clay Minerals

Although cation exchange is a universal property of soils, the extent to which different soils are able to exchange cations with solutions varies widely, ranging from a few milliequivalents (me)* to as much as 200 or more me/100 gm. The highest values are found among peaty soils because organic matter has a high exchange capacity. The exchange capacity

of inorganic soils is rarely more than 75 me/100 gm and with the vast

majority it is substantially less than 50me/100 gm.

Each constituent in the clay fraction of the soil has a cation

exchange capacity that is rather characteristic. The approximate cation

exchange capacities of the common clay minerals are shown in Table 1.

Clay Mineral	Cation Exchange Capacity (me/100gm)
Montmorillonite	80 - 150
Illite	10 - 40
Kaolinite	3 - 15
Halloysite	5 - 50
Attapulgite	20 - 30
Vermiculite	100 - 150
Chlorite	10 - 40

Table 1

Cation Exchange Capacities of the Common Clay Minerals After Grim (1953).

CHAPTER 3

IDENTIFICATION OF THE CLAY MINERALS

3.1 General

The methods of identification now available include X-ray analysis, dehydration, differential thermal analysis, optical, electron microscopic, chemical analysis, and cation exchange capacity determination. Unless a given kind of clay mineral comprises a considerable percentage of the total, none of these methods gives absolute identification or permits accurate determination of the amounts present, but by combining two or more methods, it is usually possible to determine what type of clay predominates, and in some cases to make an estimate to within 10% of the relative amounts of the different types that are present. Although only the X-ray analysis and cation exchange capacity determination were used in this investigation, all of the methods are briefly outlined below. X-ray analysis was used because it is the most precise method, the equipment was readily available, and the technique was relatively easy to learn.

3.2 X-ray Analysis

The majority of clay minerals have layer silicate structures with a marked basal cleavage. Although X-ray diffraction shows several lines that are common to all clays, the basal reflections of each clay are generally distinctive.

Hendricks et al, cited by Kelley (1948), showed that both water
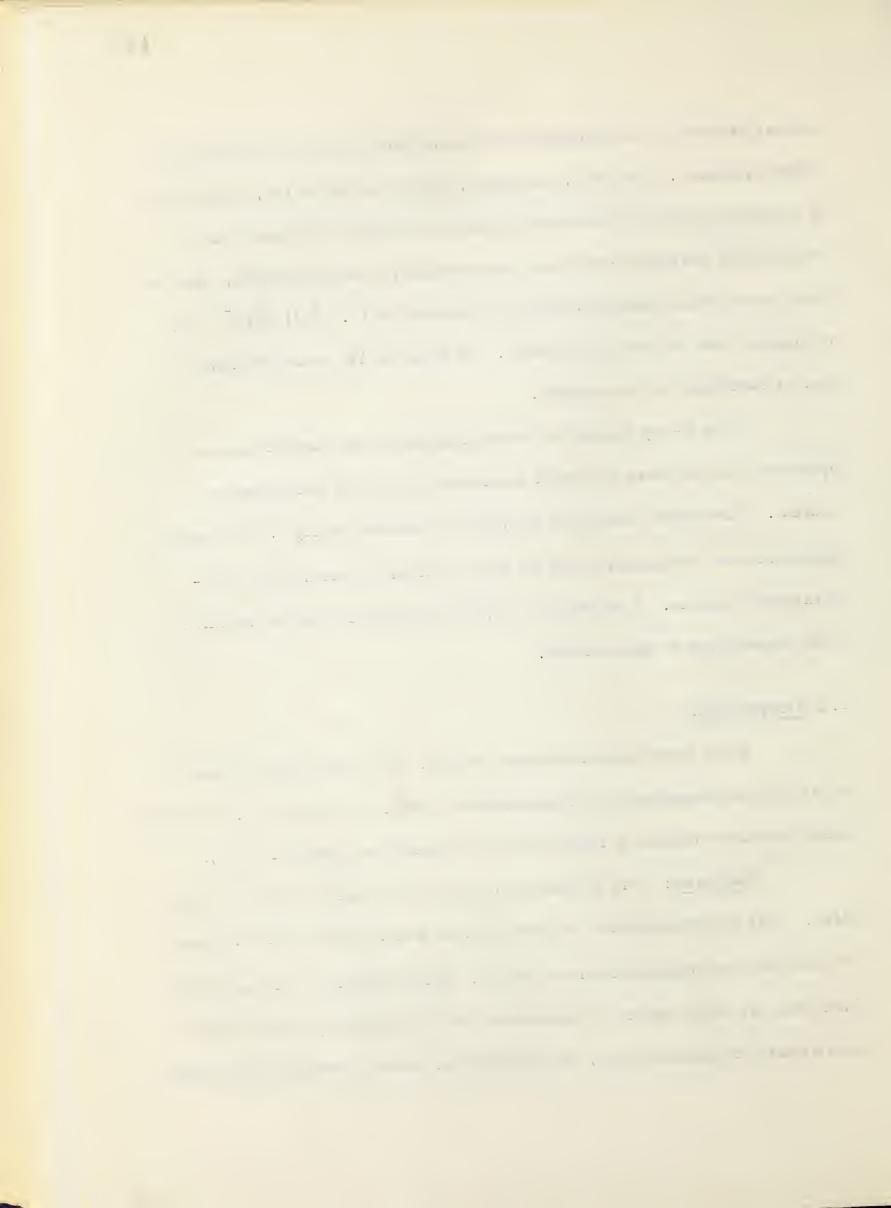
content and kind of exchangeable cation influence the basal reflections of

montmorillonite. However, MacEwan, also cited by Kelley, showed that

by treating montmorillonite with glycerol a complex is formed which

shows much sharper X-ray lines than ordinary montmorillonite, and the

first order basal reflection with this material is 17.7 $\overset{o}{A}$ (1 $\overset{o}{A}$=10^{-8} cm)

no matter what cations are present. As little as 1% montmorillonite

can be identified by this method.

The X-ray method is poorly adapted to the identification of

hydrated mica because the basal reflections vary with the moisture

content. The widest spacing of kaolinite is approximately 7.2 A^o and is

apparently not influenced either by water content or the nature of ex-

changeable cations. A minimum of 5% of the sample must be kaolinite

to be determined by this method.

3.3 Dehydration

When hydrous minerals are heated, the lattice OH ions pass

off as H_2O at temperatures characteristic of each mineral group. Adsorbed

water usually volatizes at relatively low temperature (below 150^C C).

Kaolonite: The dehydration curve of kaolonite is highly distin-

ctive. This mineral adsorbs relatively little water and its OH ions pass

off as H_2O at a temperature near 500° C. Since kaolonite contains more

than twice as much water of constitution per unit weight as either mont-

morillonite or hydrous mica, the dehydration curve of kaolonite is readily

distinguished from that of other clay types.

Montmorillonite: The pronounced dehydration characteristic of this mineral is its high water loss below 150°C. This water is adsorbed water which is chiefly held between lattice layers as discussed in section
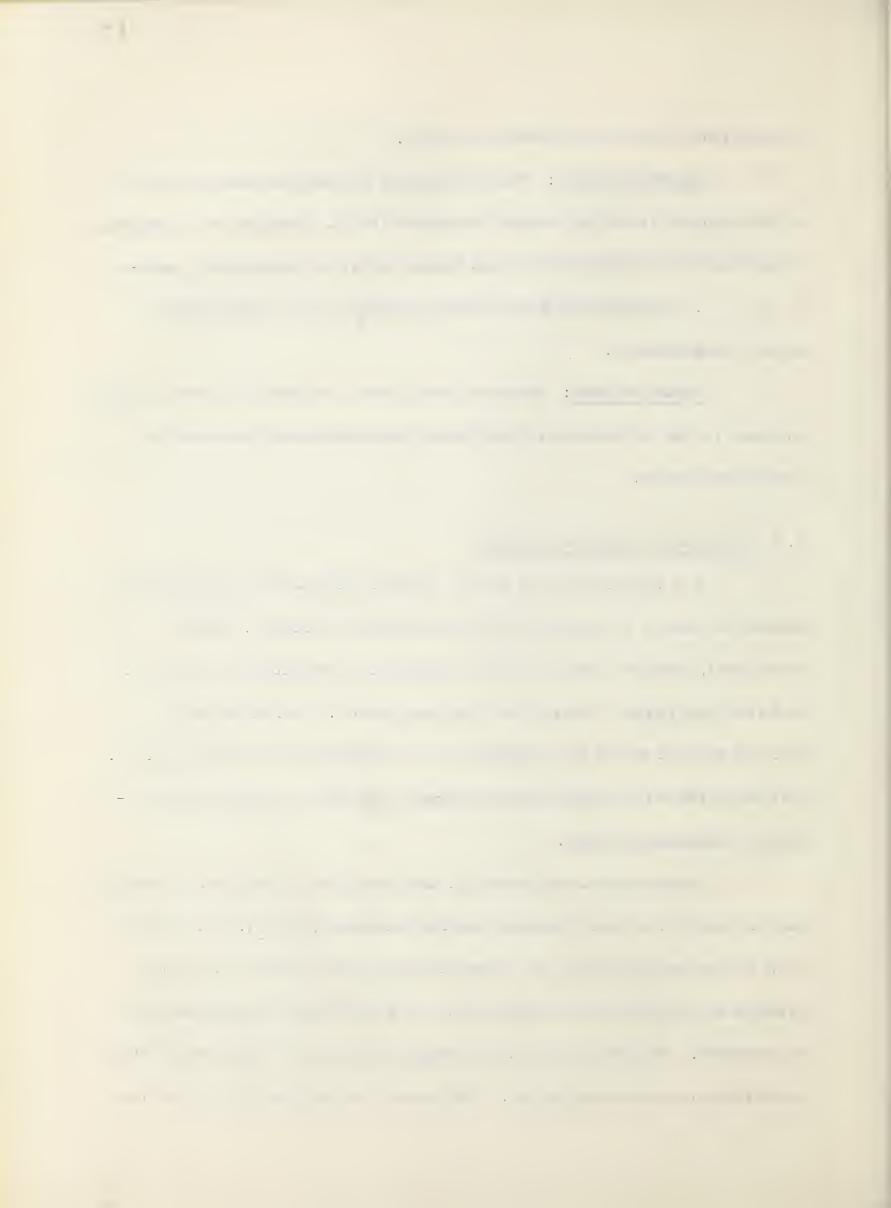
. The lattice OH ions pass off as H_2O over a wide range of higher temperatures.

Hydrated Mica: Hydrated mica gives a dehydration curve similar in shape to that of montmorillonite but with considerably less water at low temperatures.

3.4 Differential Thermal Analysis

The volatilization of water, whether adsorbed or derived from lattice OH ions is accompanied by the absorption of energy. On the other hand, energy is set free in the oxidation of carbonaceous material and also as a result of molecular rearrangements. The differential thermal method shows the temperatures at which these effects take place. The temperatures at which these reactions take place is fairly characteristic of each mineral type.

One head of a dual terminal thermocouple is placed in the sample and the other in an inert material such as Alundum (Al_2O_3). The connections are so arranged that the potentials oppose each other hence when there is no reaction in the sample there is no net heat flow and therefore no potential. Any heat effect in the sample results in a heat flow which is picked up on a recording device. The result is a straight line for no heat
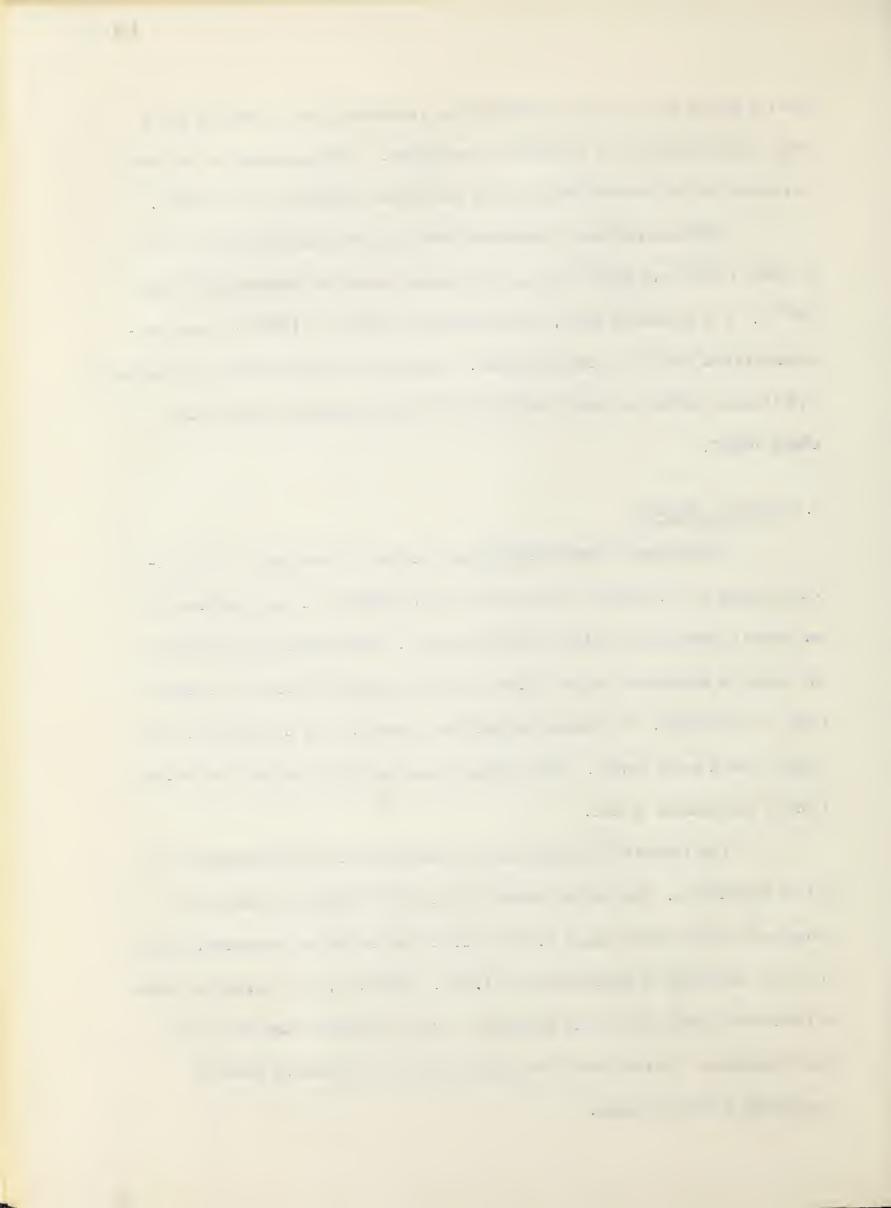
flow, a dip in the curve for endothermic reactions (loss of water) and a rise in temperature for exothermic reactions. The amplitude of the peak is related to the concentration of the particular mineral in the sample.

Montmorillonitic minerals show a marked endothermic effect at about 150°C and quite often an exothermic reaction between 800°C and 900°C. For hydrated mica, the endothermic effect at 150°C is less pronounced than that of montmorillonite. Kaolonitic minerals have a pronounced end thermic effect at about 550°C and a sharp exothermic reaction at about 900°C.

3.5 Optical Methods

The index of refraction of any medium is the ratio of the velocity oflight in a vacuum to that in the given medium. It is measured in an optical instrument called a refractometer. Measured in this manner the index of refraction is not constant but increases as the wave length of light is decreased. To obtain comparable results, it is necessary to use light of fixed wave length. The common practice is to employ the yellow light of the sodium D line.

The indices of refraction of montmorillonite and kaolonite are fairly distinctive. The alpha index of montmorillonite from bentonite commonly varies from about 1.490 to 1.530 while the corresponding value for pure kaolonite is approximately 1.560. However, the refractive index of montmorillonitic soils and kaolonitic soils is greater than that of the pure minerals. In the case of kaolonitic soil the refractive index is commonly 1.600 or more.
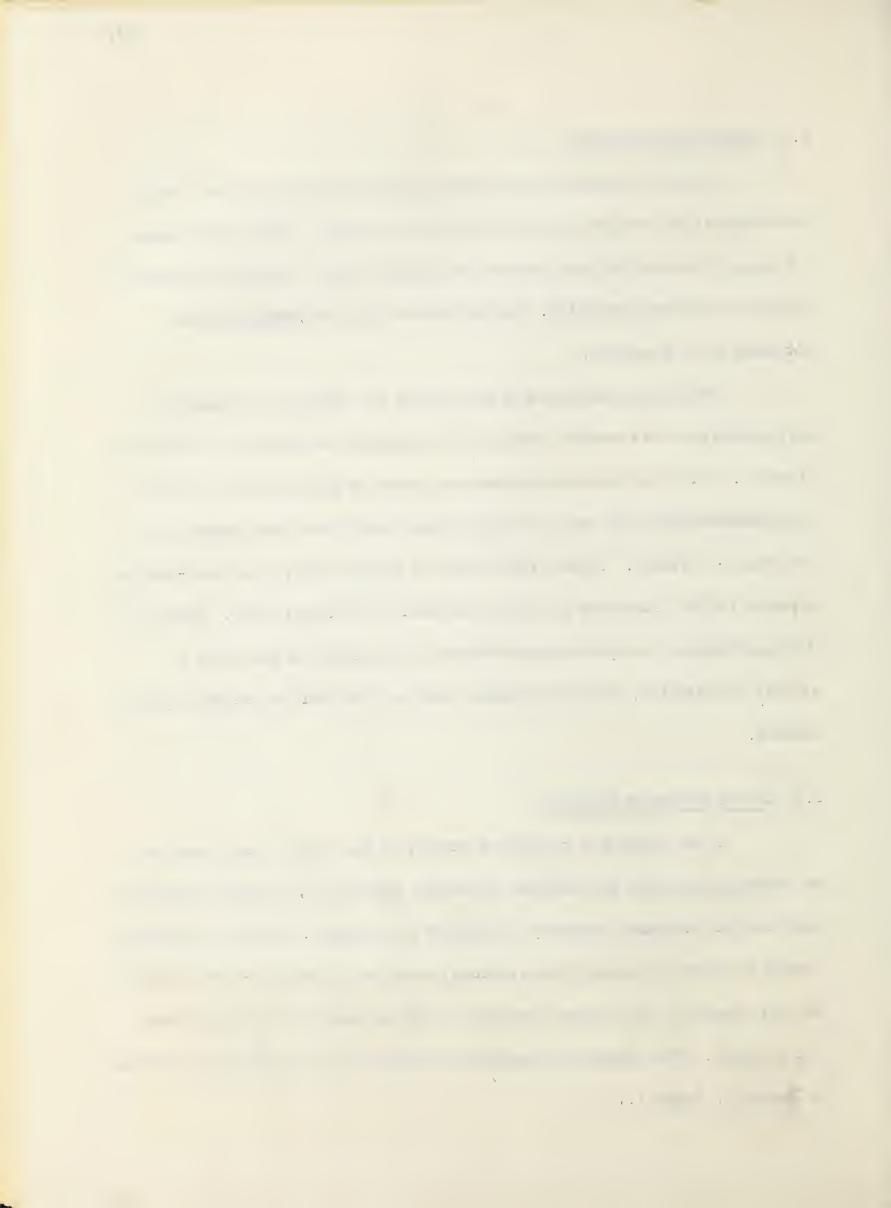
3.6 Electron Microscope

Another means of identifying some minerals is by their size and shape as determined by the electron microscope. In this instrument a beam of electrons is used instead of ordinary light to observe and photograph the colloidal particles. Magnification up to 100,000 X has been obtained by this method.

Montmorillonite and hydrous mica are difficult to identify in soil colloids by this method owing to the irregular boundaries of individual crystals. The well developed hexagonal plates of kaolonite are clearly recognizable under the electron microscope while halloysite appears as rod shaped crystals. Illites from different sources vary from lath-shaped crystals to thin flakes but are most common in the latter form. Since the size and shape of many montmorillonites is dependent on the mode of sample preparation, montmorillonite clays are difficult to classify by this method.

3.7 Cation Exchange Capacity

If the sample is composed largely of one type of clay mineral, the exchange capacity will indicate what that mineral is, but with uncertain mixtures the exchange capacity is difficult to interpret. The determination should be made on material representing a series of particle-size ranges. By this means an approximate estimate of the amount of montmorillonite can be made. The exchange capacities of common clay minerals are shown in Chapter 2, Table 1.

CHAPTER 4

IONIC ADSORPTION AND RELATED PHENOMENA

4.1 Ionic Adsorption and Particle Charge

One of the characteristics of a colloidal suspension is that the
particles carry an electric charge which may be either positive or neg-
ative. Most clay particles carry a net negative charge because of a lack
of positive charges in the crystal lattice. Adsorbed cations, which are
capable of replacement, are found on the surface of the clay mineral and
in the case of some minerals (montmorillonite group) also between the
lattice layers.

Figure 2 represents schematically a clay particle immersed in
pure water. Sufficient exchangeable cations surround the particle and
are attracted to it by the net negative charge of the clay particle in order
that the cations plus the particle constitute an electrically neutral system.
This system is designated the clay "micelle". The ions and water within
the micelle constitute the "Helmholtz double layer". The inner layer is
part of the wall of the particle. The outer layer is of opposite sign and
is at a distance of several molecular dimensions from the inner. The
cations in the outer layer can be replaced by other cations in the process
of cationic exchange.
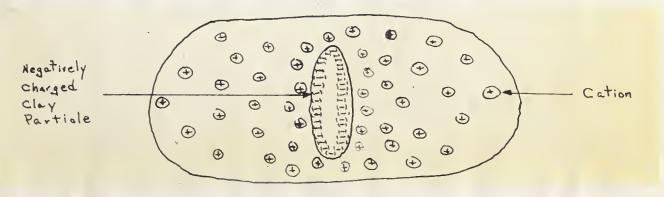
Fig. 2 The Clay Micelle in Pure Water
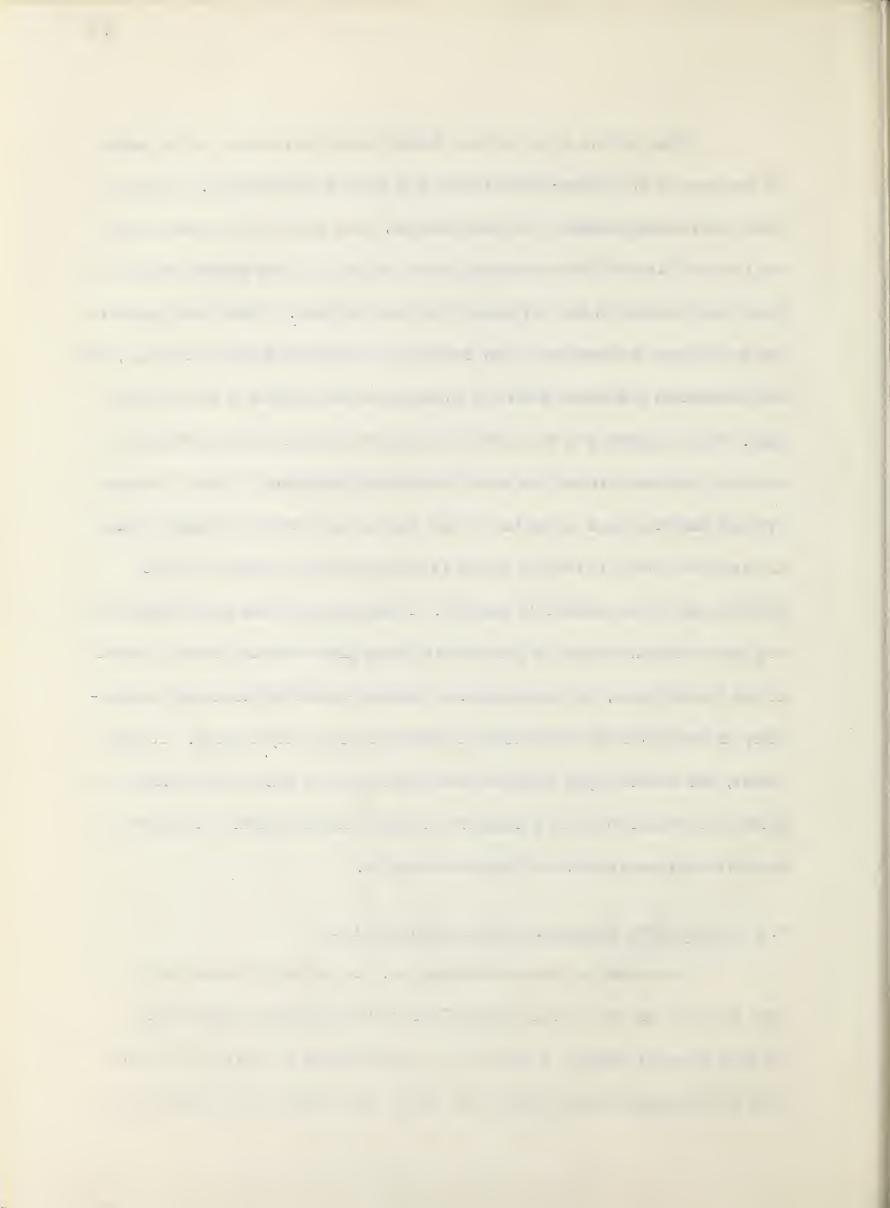
The cations in the diffuse double layer move about in the water as pictured in the Debye-Huckel theory of strong electrolytes. Since the water molecules possess a dipole moment, they tend to be oriented along the lines of electric force radiating from each ion in the diffuse layer and from each charge on the surface of the clay particle. Every clay particle and ion is thus surrounded by an envelope of oriented water molecules, and the orientation manifests itself as an apparent adsorption of water by the clay. Some cations are so close to a negative charge on the surface of the clay particle that the two water envelopes belonging to these charges overlap and the water molecles in this region are strongly oriented since the negative end of the water dipole is attracted to the cation and the positive end to the particle's surface. If the clay particle were immersed in a salt solution instead of pure water, then anions would also be present in the double layer, but the number of cations would be increased accordingly in order that the micelle still remain electrically neutral. In other words, the double layer includes that portion of the water surrounding the particle in which there is a negative electric field requiring an excess of positive charges relative to negative charges.

4.2 The Relative Replacing Power of the Cations

According to most investigators, the attraction between the clay particle and the cations obeys Coulomb's law which requires that for ions of equal charge, a small ion is attracted by a greater force and held more tightly than a larger ion. Since all cations are hydrated in the

soil water system, it is the size of the hydrated ion which governs the

force of attraction expressed by Coulomb's law. Jenny, cited by Baver

(1958), gave the values shown in Table 2 for hydrated ca ion radii.

Cation	Radius (Angstrom Units)
Li	10.03
Na	7.90
K	5.32
NH_4	5.37

Table 2: Radii of Hydrated Cations

Since the K ion is smaller than the Na ion, by Coulomb's law,

the K ion is more strongly adsorbed than the Na ion.

It has been found that Hydrogen tends to act as a divalent or

trivalent ion and is very strongly adsorbed but this may be explained by

consideration of the forces of attraction. There is a tendency for ad-

sorbed H^+ to form OH^- with the O^{--} of the crystal lattice because of

the great attraction between H^+ and O^{--}. In fact H_2O may even be formed.

Research by Schachtschabel (1940), cited by Mielenz (1955),

demonstrates that the relative replacing power of the cation also depends

on the concentration of the solution and the type of clay mineral. Based

upon treatment of NH_4 saturated clay minerals, he found that the relative

ease of replacement of NH_4 at various concentrations of replacing cations

was as shown in Table 3.

Concentration of Cation in Solution (me/100 gm)	Replacing Power of Cations
	NH$_4$ Montmorillonite
1	Na < K < H < Mg < Ca
10	Na < H < K < Mg < Ca
100	Na < Ca < Mg < H < K
	NH$_4$ Muscovite
1	Na < Mg < Ca < K < H
10	Mg < Ca < Na < K < H
100	Mg < Ca < Na < K < H
	NH$_4$ Permutite
1	Mg < Na < K < Ca < H.
10	Mg < Na < Ca < K < H
100	Mg < Ca < Na < K < H

Table 3

Replacing Power of Cations
From Schachtschabel (1940)

It will be noticed that the K and Na ions observe Coulomb's law in all cases. That is, the K ion being smaller than the Na ion has greater replacing power than the Na ion. From similar studies, Kelley (1948) concludes that when a polyvalent ion is replacing a monovalent ion, the exchange power increases as the concentration of the solution decreases, whereas when a monovalent ion is replacing a polyvalent ion, the exchange power increases with the solution concentration. Thus, for instance, with a very dilute solution of NaOH percolating through a Ca soil, very little Ca will be replaced by Na. The principal result of all studies on the
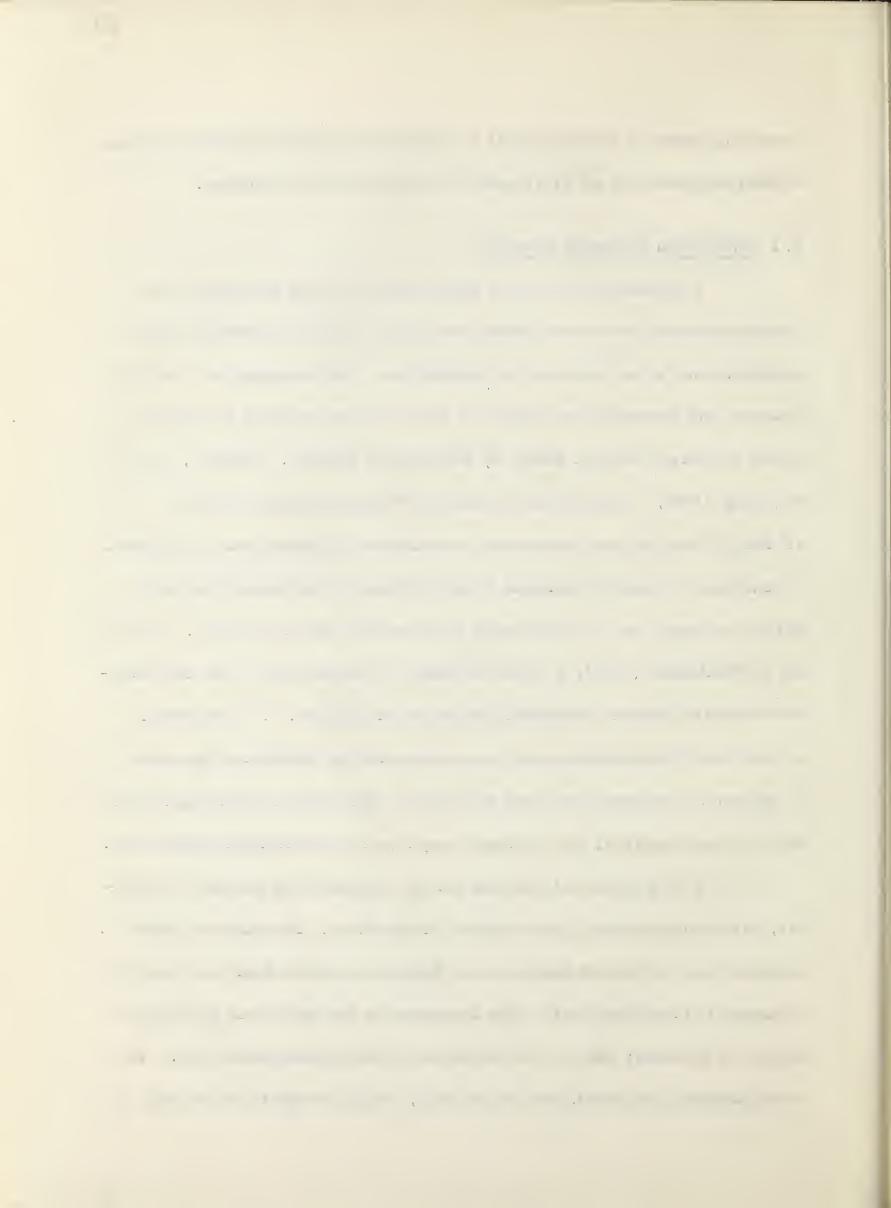
replacing power of cations is that no one order of replaceability of cations is characteristic for all clays and all concentrations of solution.

4.3 The Cation Exchange Reaction

Wilklander (1955) cites experiments by Way and others which demonstrate that the rate of cation exchange in soils is generally rapid, requiring only a few minutes for equilibrium. The exchange is a surface reaction and procedes just as fast as ions from the solution are applied to the exchange material either by diffusion or shaking. Gedroiz, cited by Kelley (1948), reported that in shaking 50 grams of soil and 500 cc of $1N$ NH_4Cl that the equilibrium was established by shaking only 3 minutes. A condition for rapid attainment of equilibrium is that the soil be moist before exchange, as the moistening process may take some time. According to Wilklander (1955), a rapid exchange is feasible only if the exchangeable ions are directly accessible to the ion in solution. It is important to note that if the exchange has to be preceeded by diffusion of the ions to the inner surfaces of the clay particles or the interior of the aggregates with low permeability, the exchange may require considerably more time.

With soils in solution the rate is very high for kaolonite minerals, the exchange taking place mainly on the edges. In montmorillonite minerals most of the exchange occurs between the sheets and the rate of exchange is therefore likely to be dependent on the interlayer spacing or degree of swelling; that is, on the nature of the exchangeable ions. In swelled montmorillonite, the rate is high, though probably not so high as

in kaolonite. In illite the rate of exchange is slower because the exchange

takes place along the edges between the narrow interlayer surfaces. It

must be emphasized that the rates just described are for soils in solution.
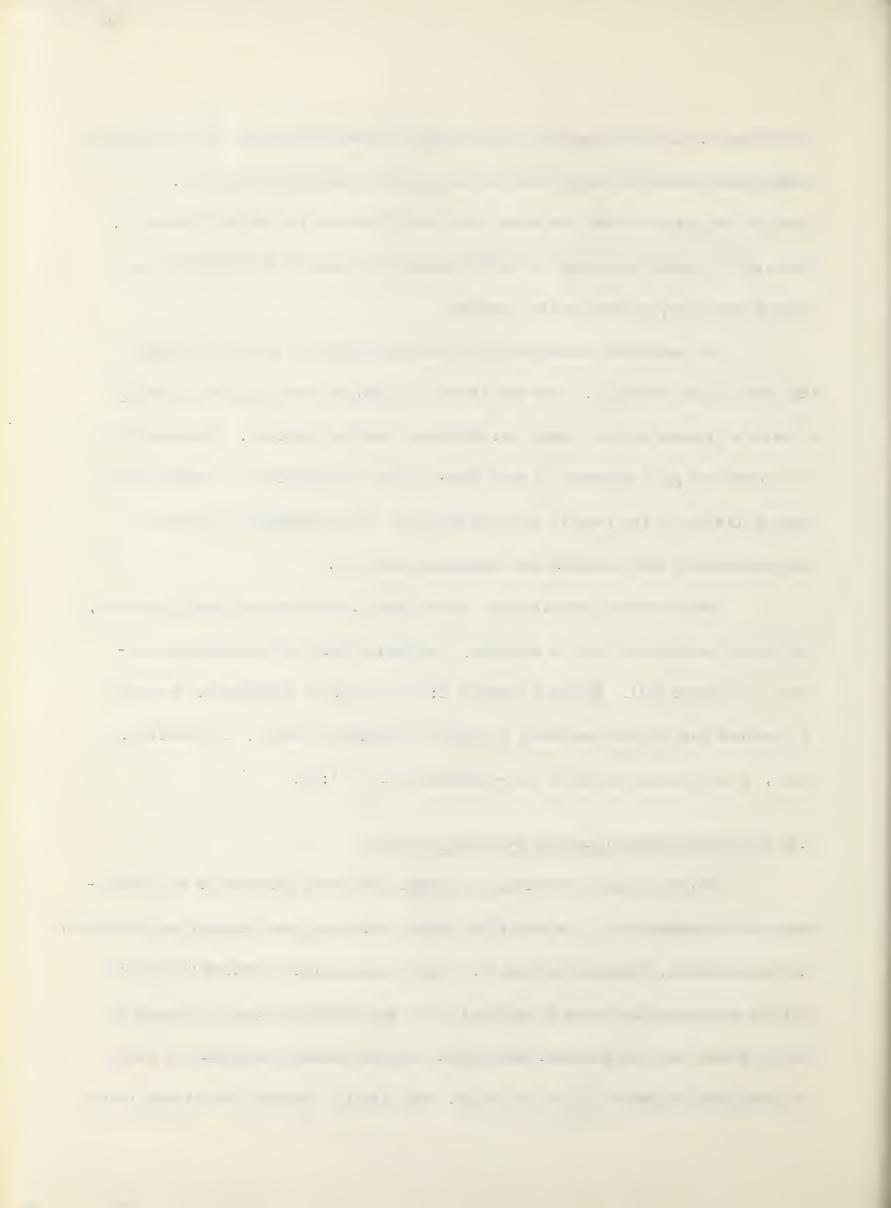
The rate of cation exchange for soils in place is likely to be very slow no

matter what clay minerals are present.

An increase in temperature has been found to increase slightly

the rate of ion exchange. For the slower exchange, temperature is likely

to have a greater effect, since ion diffusion may be involved. However, it

is considered poor practice to heat above room temperature as heating may

induce fixation of the ions to varying degrees, thus changing the relative

ion proportions and lowering the exchange capacity.

Many investigations have shown that in a cation exchange reaction,

the lower the ratio of soil to solution, the higher the cation exchange cap-

acity of a given soil. Below a ratio of 1:100 a point of diminishing returns

is reached and further increase in cation exchange is small. In laboratory

tests, it is common to use a soil-solution ratio of 1:50.

4.4 Ion Concentration and the Swelling of Clays

When an aqueous solution is separated from pure water by a semi-

permeable membrane, it is found that water tends to pass through the membrane

into the solution, thereby diluting it. This phenomenon is called "osmosis"

and the pressure that must be applied to the solution in order to prevent the

flow of water into the solution through the impermeable membrane is called

the "osmotic pressure" of the solution. Similarily, osmotic pressures can be

developed between two solutions of unequal ion concentration.

Ladd (1960) describes consolidation-rebound tests on fraction-ated samples of pure clay minerals that showed an osmotic repulsive pres-sure is developed between clay particles that causes rebound or swelling when the effective stress on the sample is reduced. It was found that the repulsive pressure is proportional to the difference in ion concentration in the clay micelle and that in the "free" pore water.

To explain the repulsive pressure in saturated clays, the hypothesis is that the electric field (Helmholtz double layer) around the negatively char-ged clay particle acts as a semi-permeable membrane in that it will allow water to enter the double layer but will not allow exchangeable cations to leave the double layer except on a replacement basis. In most clays, be-cause of the exchangeable cations, the concentration of ions in the double-layer water is greater than the concentration of ions in the pore fluid. The result of this difference in ion concentration is that water tends to flow into the clay micelle from the pore fluid and an effective stress is required to prevent an increase in interparticle spacing (swelling). Results from labor-atory consolidation-rebound tests (Warkentin et al, 1957) on saturated samples with various exchangeable-cations and pore water ion concentrations sub-stantiate this theory.

The application of this knowledge of the swelling behaviour of saturated clays may permit the reduction of swelling in clays by:

(1) The replacement of low valency exchangeable cations by higher valency cations thus reducing the concentration of ions in the double layer.

(2) Leaching clays with salt solutions of sufficient strength to increase concentration in the free pore fluid.

CHAPTER 5
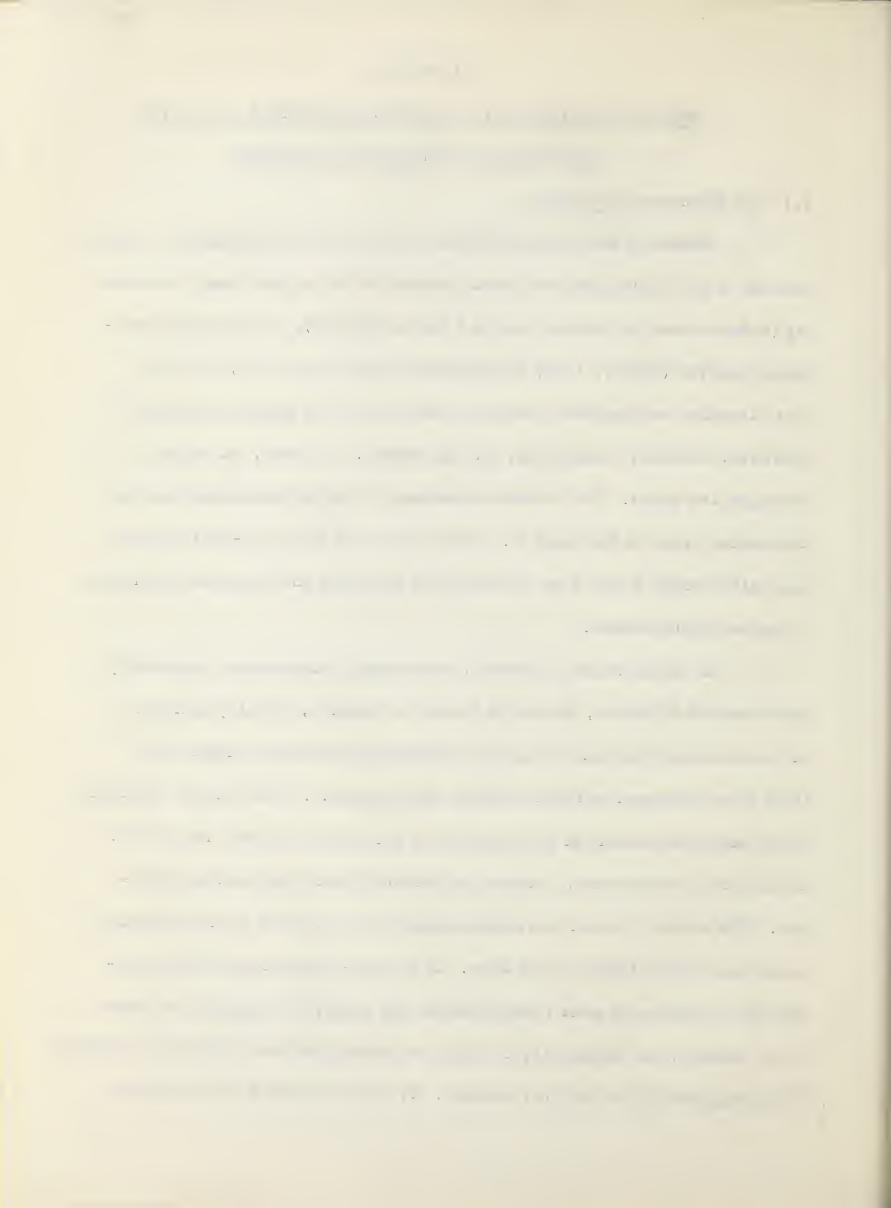
THE DETERMINATION OF CATION EXCHANGE CAPACITY

AND THE EXCHANGEABLE CATIONS

5.1 The Abundance of Cations

Studies of the relative amounts of the various exchangeable cations present in soils have generally been confined to the current zone of weathering (a depth from the surface of 3 to 5 feet in Alberta). A world wide statistical analysis (Kelley, 1948) would indicate that in this zone, the four most abundant exchangeable cations in the soils of the humid regions are hydrogen, calcium, magnesium, and potassium. Of these, all except hydrogen are bases. The relative abundance of the exchangeable bases in descending order is Ca> Mg> K. Soils of the arid and semi-arid regions generally contain little or no exchangeable hydrogen and important quantities of exchangeable sodium.

In the province of Alberta, according to information supplied by the Alberta Soil Survey, Research Council of Alberta, the clay minerals in the soil below the zone of current weathering generally contain very little or no hydrogen and little sodium and potassium. The relative abundance of exchangeable cations in this material is generally Ca > Mg> Na > K > H. In the zone of weathering, calcium is currently being replaced by hydrogen. The extent to which this replacement has progressed is predominantly dependent on the climate in the area. In the sub-humid areas of the province (precipitation greater than 15 inches per year), for example the Peace River district, the surface layer of the soil quite often has a higher percentage of exchangeable hydrogen than calcium. In the drier areas of the province

there is generally less hydrogen because of slower soil development.

5.2 General Principles

Regardless of the kind of exchange material being dealt with, the quantitive determination of the exchangeable cations depends on the fulfillment of three conditions: (1) complete replacement of all exchangeable cations by some cation which is not present in the sample, (2) accurate analysis of the solution obtained, (3) determination of, and suitable correction for, the cations that pass into solution from soluble substances, or by decomposition of some substance or sample. The accurate determination of truly exchangeable Mg in many soil types is more difficult than that of the other cations. The apparent reason is that some soils contain Mg minerals which tend to decompose to some extent in the course of the determination.

In view of solubility and decomposition effects, the exchange capacity is determined by measuring the cations adsorbed from the solution rather than the amount of cations that are brought into solution from the soil. It is important to emphasize the fact that the exchangeable cations can be replaced by H ions as well as other ions. For this reason the salt solution should be neutral (pH 7)*. The pH of the solution must always be stated since the total amount of cations that can be exchanged is likely to vary with the pH.

The exchange reaction is subject to the principle of chemical equilibrium. Therefore the cations brought into solution by exchange, or

by any other process, must be removed from contact with the soil; otherwise the replacement will not be complete. Hence for complete exchange the sample should be leached with the solution until the solution passes through unchanged.

5.3 Methods

Dozens of methods, some of which differ only slightly, have been proposed for this determination. All of them involve the replacement of the exchangeable cations followed by analysis of the resulting solution. According to Kelley (1948), the amount of NH_4 adsorbed upon leaching the soil thoroughly with a neutral ammonium salt solution is probably as accurate a measure of cation exchange capacity at pH7 as can be found.

NH_4 acetate, being a salt of a weak base and a weak acid, does not hydrolize appreciably, and its solution is well buffered. Therefore, the replacement of H ions by NH_4 ions does not greatly alter the pH of the solution. In addition, the unused NH_4 acetate of the solution is easily removed by leaching with neutral methyl or ethyl alcohol, and this facilitates the analysis of the residue.

The technique of the methods used in this investigation is described in detail in Appendices I, II, and III. Briefly, the determination consists of leaching the soil with normal neutral ammonium acetate until the exchangeable cations are completely replaced by NH_4 ions. The replaced ions were determined by analysis of the leachate using a flame photometer and titration. The adsorbed NH_4 (exchange capacity) was

determined in the same sample by distillation in the presence of an acid

after having first removed the occluded ammonium acetate by leaching

with neutral methyl or ethyl alcohol.

CHAPTER 6

PREVIOUS STUDIES OF CHANGES INDUCED IN THE PHYSICAL
PROPERTIES OF SOIL BY CATION EXCHANGE

6.1 General

Investigations by Baver (1928), Baver and Winterkorn (1935),
Sullivan (1939), Lambe (1954), and Matsuo (1957) show that the nature of
adsorbed cations influence such soil physical properties as plasticity,
permeability, shrinkage, swelling, consolidation, and strength. Lambe
(1954) divides the cations into two general categories according to their
effect on the soil: flocculants and dispersants.

Flocculating or aggregating cations markedly increase soil
porosity and permeability and reduce cohesiveness. The Ca cation is one
of this type.

Dispersing cations, when added to fine grained soil in minute
amounts, cause abnormally high fluidity at low water contents, low per-
meability and more than normal consolidation. Most dispersants are also
water proofers since they reduce the amount of water a soil takes up. In
this regard, Lambe (1954) found that dispersants decrease the formation
of ice lenses in fine grained soils, thus reducing the frost susceptibility
of such soils. The Na cation is an active dispersant in soils.

Most soils are granular when Ca saturated. On the other hand,
soils containing exchangeable Na cations are dispersed and relatively
impermeable. Ca cations seem to bind the fine-sized particles into

aggregates, whereas Na cations cause dispersion. Toth (1955) suggests

a possible explanation is that exchangeable Ca cations on the surface of

the crystals, being divalent, possibly link adjacent particles together by

sharing their charges between particles, thus building up aggregates.

The Na cation, being monovalent, is unable to do this. However, it seems

that once a clay is highly dispersed, as by leaching with NaCl solution,

the fine-sized particles do not always become reoriented immediately

on replacement of Na cations by Ca cations. As yet there is no explana-

tion of this phenomena.

6.2 Shrinkage and Swelling

Baver and Winterkorn, cited by Mielenz (1955), studied the

effect of exchangeable cations on the swelling of the montmorillonite

group of clay minerals. For Wyoming bentonite they observed decreased

swelling in the sequence:

$$Na > K > Ca > Mg > H.$$

For beidellite the sequence was found to be:

$$Na > Ca > H > K$$

It will be noticed that according to the osmotic pressure theory of

swelling (section 4.4) the K ion, being monovalent, should cause more

swelling than Ca or Ng. This is not the case for beidellite. The ex-

planation of this phenomenon is that K in the interlayer spacings of

beidellite apparently acts as a binding agent thus preventing normal ex-

pansion of the lattice.

In the drying of clays, shrinkage is more pronounced in the

montmorillonite type clays than those of the illite or kaolonite group

because of the typically greater fineness, thicker adsorbed water films on the periphery of crystals, and interstitial water. Winterkorn and Moorman (1941) report a range of shrinkage limit of a beidellite soil from 19.4 to 11.8 percent in the following order:

$$K > H > Mg \text{ - } Ca > Na$$

Again the misplaced position of K in the above series demonstrates the binding of the lattice by K in the interlayer spacings. Shrinkage ratio varied from 2.08 to 1.80 in the order:

$$Na > Mg > Ca > H > K.$$

6.3 Plasticity

Winterkorn and Moorman (1941) have proved the influence of exchangeable cations on the plasticity of a beidellite soil. With intro-duction of Na, Ca, Al, Mg, H, and K in portions of the soil, values ranged as follows:

Liquid Limit 52.8 to 88

Plastic Limit 24.8 to 27.7

Plasticity Index 25.1 to 62.6

The following relative values of the limits were found:

Liquid Limit: Na > Ca > Al > Mg ₌ H > K

Plastic Limit: K > Ca > Al > Mg ₌ Na > H

Plasticity Index: Na > Ca > Al > H > Mg > K

Data, cited by Mielenz (1955), and compiled from several sources give the order of decreasing liquid and plastic limit for montmorillonite as:

$$Na > H > K > Ca > Mg$$

The change in liquid and plastic limits is far less marked for kaolonite, illite and beidellite. Na influences properties of clays far beyond relative abundance in the exchange positions. According to Winterkorn (1953), if as little as 15% of the exchange capacity is occupied by Na, montmorillonite exhibits the properties of homionic Na montmorillonite.

6.4 Permeability

Winterkorn and Moorman (1941), in tests on remoulded beidellite clay, found the permeability of the homionic modifications in the following order:

$$K > H = Ca = Mg > Na$$

The permeability of treated kaolonite is similarly affected by exchange of ions. It decreases in the series:

$$Ca > H > Na.$$

6.5 Strength

In studies of montmorillonite compacted at optimum moisture content, Samuels, cited by Mielenz (1955), demonstrated shear resistance with the clay modifications in the series:

$$Al > Ca > Na.$$

Shear resistance of Na, Ca, and Al modifications of kaolonite is essentially identical with that of montmorillonite. Unconfined compressive strength tests conducted on Na and Ca montmorillonite modifications demonstrated the relationship of compressive strength to moisture content. At a moisture content less than 50%, the Na clay showed the

greater strength; with moisture content between 50% and 75%, the strength was about equal: and at moisture content over 75% the Na clay again exhibited greater strength. The comparatively high strength of the Na clay at moisture content below 50% probably was due to cohesion of the specimen produced by tension in the water films. With moisture content in the range of 75% to 143%, the Ca clay approaches the liquid limit, whereas throughout this range the Na clay was always well below the liquid limit. For unconfined tests with moisture content equivalent to one-fourth that of the respective liquid limits, the strength of natural Na montmorillonite was .14 T/ft^2 and that of the Ca modification was 1.6 T/ft^2. These last two tests are of no real significance however, because strength is dependent on the relative location of the moisture content of the soil with reference to the liquid and plastic limits. In the case of the Na soil the moisture content of the test specimen may have been midway between the liquid and plastic limit whereas the moisture content of the Ca specimen may have been equal to the plastic limit.

Winterkorn and Moorman (1941) conducted drained triaxial shear tests on modified beidellite soils compacted to maximum density at optimum moisture content. Be replacing naturally occuring H, Ca, and Na in the beidellite with K, they increased the angle of friction from 19° to 22°.

In a series of torsion shear tests on remoulded Lawrence clay, Sullivan (1939) found that the shear strength, as indicated by maximum torque required for failure, varied with the nature of the exchangeable

cation. He found the order of decreasing maximum torque was:

$$NH_4 > H > K > Fe > Al > Mg > Ba$$

over a range of 400 to 1300 gm/cm at 23% moisture.

In a study of the cause of a slope failure in Japan, Matsuo (1957) found that the ground-water at the base of the slope contained considerably more Ca than the rainwater. At the time of the tests 3/4 of the exchangeable cations in the soil were Ca and since it appeared that Ca was being leached out of the soil it was presumed that originally the concentration of Ca in the soil was much higher. A series of shear tests on both the natural soil and the same soil,Ca saturated, were conducted and on the basis of these strengths, the factor of safety for the slope was computed. The factor of safety for the Ca saturated soil was 1.3, whereas that of the natural soil was 0.6.

6.6 Consolidation

The rate of consolidation, being controlled by permeability, is also affected by the adsorbed cations. Those cations which produce lower permeabilities cause slower rates of consolidation.

The dependence of the amount of consolidation upon exchangeable cations has also been demonstrated. For beidellite soil, Winterkorn and Moorman (1941) found the amount of consolidation under a given load, in decreasing order was:

$$Na > Ca > Mg > K > H$$

For montmorillonite the order of consolidation of the modifications was:

$$Na > Ca.$$

CHAPTER 7

PREPARATION OF SOIL FOR TESTING

7.1 Soil Used in the Investigation

The tests outlined in this thesis were conducted on a clay shale

obtained from the east side of the Dunvegan Creek valley near its con-

fluence with the Peace River at Dunvegan, Alberta. Two similar series

of tests were conducted. The soil for the first series of tests came from

Hole 140. Equal parts of soil from depths 75', 85', 105', and 115' were

thoroughly mixed to make up a homogeneous sample representative of

the soil between 75' and 115'. The second series of tests were conducted

on soil from Test Hole U of A, drilled purposely for cation investi-

gations by the Research Council of Alberta. A continuous sample from

68' to 75' was cored. Equal parts of soil from each 1 foot core were

used to make up a sample representative of this depth. In addition three

undisturbed samples from depths 71', 73', and 75' were obtained for con-

solidation tests. In all, approximately 50 lbs. of clay was used in the

investigation.

The clay shale used for this investigation is typical of shales

occurring over a wide area in glacio-lacustrine basins in north-eastern

British Columbia, northern Alberta, and the foothills section of the

Yukon Territory. These shales were formed from a well sorted

stratified deposit composed principally of clay-size particles that were

sedimented in the large lakes that occupied these basins during inter-glacial and post-glacial times. Because of the removal of ice load and the continual erosion since the last retreat of the ice, these shales now exist at overburden pressures much less than occurred during their formation. Because of the reduced intergranular stress, the clay minerals in the shales swell by taking up water when it is available, thus reverting the shale to its original form - a clay of high plasticity.

Perhaps the most striking result of the loss of strength which accompanies the swelling of these shales has been the formation of very wide stream and river valleys with side slopes as low as 1:10. The valleys in these glacio-lacustrine basins are currently being widened by landslides and slumps which follow the downcutting.

7.2 Preparation of Samples of Homogeneous Soil

After the clay had been obtained from the field, each specimen was extruded from the thin wall sampling tubes and sliced into many small fragments. These fragments were immediately placed in quart size glass sealers, labelled as to depth, and stored in the 75% constant humidity room to maintain them as close as possible at natural moisture content. Since the largest suitable mixer had only a 15 qt. capacity, the largest sample that could be mixed at one time was 3.5 kg. Consequently, re-presentative portions from each depth were combined to make up a 3.5 kg. batch and this batch was made into a slurry by mixing with distilled water in the mixer shown in photograph 1. As more soil was required, further

PHOTOGRAPH 1 - 15 QUART CAPACITY SOIL MIXER

representative samples from each depth were combined and mixed to a

slurry in the mixer. The slurries were stored in open pails in the

moist room and were stirred each day until required.

7.3 Preparation of Modified Soils

One-sixth of the total slurry from each test hole was left un-

treated and is referred to as natural soil. The moisture content of the

natural soil was reduced to near the liquid limit from the slurry form by

vacuum filtration and the soil was stored in tin containers in the moist

room. The method used in making the different cationic modified soils

was similar to that used by Sullivan (1939). Sullivan suggested that as

a starting point, and as a basis for comparison, it was desirable to

convert the clay to hydrogen clay. Hydrogen clays are converted to the

other forms quite readily, and if the reagent used is an hydroxide or

an oxide, the reaction product with hydrogen clay is water.

Five-sixths of the total slurry was treated with hydrocholoric

acid in an attempt to replace all exchangeable cations with hydrogen.

A volume in c.c. of hydrochloric acid numerically equal to the weight of

the soil in grams, was added for this purpose. From the results of the

determination of the cation exchange capacity, the normality of hydro-

chloric acid necessary to transform the natural clay into hydrogen clay

was calculated. This calculation is identical in form to that outlined

below for Na clay. A quantity of acid in excess of that needed for com-

plete cation exchange was added to give a resulting normality to the

slurry of 0.05 N HCl. Since hydrochloric acid would attack the metal mixing bowl and mixer, a plastic pail was used as the mixing bowl and a metal mixer coated with neoprene was used.

The raw slurry was placed in the mixer, hydrochloric acid was added, and the slurry was stirred for 4 to 6 hours and then allowed to stand overnight. At the end of this time the clear supernatant liquid was decanted and the remaining solution was removed by vacuum filtration using the vacuum filter shown in photograph 2. The residue was then washed twice by mixing with distilled water for 4 to 6 hours each time and the liquid was removed by decantation and filtration after each mixing. A volume of distilled water equal in weight to the soil was used in each washing. After the final wash the moisture content was reduced to near the liquid limit and the clay was stored in air tight cans in the moist room. Because of the low permeability of the clay and the resulting slow filtration process, it required 6 to 7 days to prepare a 3.5 kg. sample of Hydrogen clay by this method.

Conversion from the hydrogen modified soil to the Na, Ca, Mg, and K modifications was accomplished by mixing the soil with either sodium hydroxide (NaOH), calcium hydroxide $Ca(OH)_2$, magnesium oxide (MgO), or potassium hydroxide (KOH). The method used was identical for each modification. Generally 600 gms of each modification was pre-pared. As an example, the procedure for preparing the Na modification is described below. Na clay was formed from H clay by dissolving a predetermined amount of NaOH in an amount of water about equal in

PHOTOGRAPH 2 - VACUUM FILTER

weight to the clay. The amount of NaOH required to transform the H clay into Na clay was determined from the cation exchange capacity results. The formula for determining the amount of a cation required to provide complete saturation of a soil with that cation is:

$$A_1 = \frac{c \times W \times N_1}{V \times 1000 \times 100}$$

where A_1 = weight of cation in grams
c = cation exchange capacity in me/100 gms
W = weight of air dry soil in grams
N_1 = atomic weight of cation
V = valency of the cation

Assuming a cation exchange capacity of 40 me/100 gm and 600 gms. of dry soil, the amount of Na ion required for complete cation exchange is:

$$A_1 = \frac{40 \times 600 \times 23}{1 \times 1000 \times 100} = 5.5 \text{ gms}$$

Since the reagent used is NaOH, the amount of NaOH required (R_1) is equal to the weight of Na ion required multiplied by the molecular weight of NaOH divided by the atomic weight of Na. In this case,

$$R_1 = \frac{5.5 \times (23 + 17)}{23} = 9.6 \text{ gm NaOH}$$

The clay and dilute NaOH solution were mixed thoroughly in the mixer for 2 to 3 hours. In the case of soil from the University of Alberta Test Hole, the resulting slurry was stored in the moist room in 1/2 gal. sealed glass containers and shaken occasionally. As soil was required for testing, a sample was poured from the container and the moisture content was reduced to near the liquid limit by vacuum filtration in 6 to 12 hours. In the case of soil from Test Hole 140, the slurry was poured into 2 lb honey tins immediately after mixing, was allowed to dry, with

occasional stirring, to near the liquid limit and was then sealed in the

tins and stored in the moist room. The time required for drying was 8

to 15 days. Samples for testing were removed from the air tight tins as

required.

CHAPTER 8

CLASSIFICATION TESTS

8.1 General

The untreated homogeneous soil mixtures from both the U of A

Test Hole and Test Hole 140 were subjected to the following classifi-

cation tests: - specific gravity

- grain size analyses

- determination of clay minerals by X-ray diffraction

- cation exchange capacity and the exchangeable cations

- Atterberg limits

The test procedure used in the investigation and the test results are

described below. The results of the classification tests are shown in

Table 4.

8.2 Specific Gravity

The standard method of test for specific gravity of soils,

ASTM Designation D 854-52, was used in this investigation. The

natural homogeneous soil mixtures were prepared according to the

method outlined in Section 7.2. Five hundred ml volumetric flasks were

used to reduce the percentage error to a minimum. The data sheets

are shown on Plates 12 and 13 in Appendix IV.

8.3 Grain Size Analyses

ASTM method D 422-54T was used for grain size analyses.

Classification	Soil Mix from Test Hole 140	Soil Mix from Test Hole U of A
Specific gravity	2.73	2.80
Grain size distribution		
% sand sizes M.I.T.	3	5
% silt sizes M.I.T.	24	23
% clay sizes >0.2 micron	35	32
<0.2 micron	38	40
Atterberg limits		
Liquid limit	83.2	81.7
Plastic limit	29.9	30.4
Plasticity index	53.3	51.3
Shrinkage limit	18.4	16.6
Clay mineralss		
% montmorillonite	10 – 20	25 – 35
% illite	30 – 45	25 – 35
% chlorite	30 – 45	0
% kaolonite	5 – 15	25 – 35
Cation exchange capacity	23.1	26.3
Exchangeable cations		
% Na	6	7
% Ca	63	65
% Mg	26	21
% K	5	7

Table 4

Results of Classification Tests on Natural Soil

The natural homogeneous soil mixtures used in these analyses were pre-
pared according to the method outlined in Section 7.2. Two analyses
were performed on each soil. The data sheets and grain size curves are
shown on plates 14 to 19 incl. in Appendix IV. The results are summa-
rized in Table 4. It is significant to note that between 70% and 75% of
the soils are clay sizes (finer than 2 micron).

8.4 Determination of the Clay Minerals by X-ray Diffraction

The method of identifying clay minerals by measuring the thick-
ness of structural layers using the X-ray diffraction technique was
briefly outlined in Section 3.2. To enhance basal reflection of X-rays
and reduce other reflections, thus allowing easier interpretation of the
basal reflections, it is desireable to use oriented particles, which for
the platy clay minerals can be obtained by sedimentation.

Accordingly, suspensions of the homogeneous soil from Test
Hole 140 and Test Hole U of A were prepared in the same manner as for
grain size analyses. When the hydrometer method indicated that the sand
and silt sizes had settled out, samples of the clay suspensions were re-
moved from the 1000 cc cylinders by means of a glass tube, and stored
in test tubes. Approximately 0.5 cc of each of these suspensions were
then allowed to sediment onto each of 3 glass plates, requiring 3 to 4 days
to sediment and dry completely. A second series of plates was prepared
but for these the sedimentation time was reduced to 1/2 hour by sedi-
menting onto a porous porcelain plate which was subjected to a vacuum

on the underside.

To allow quantitative identification of clay minerals when more than one type of clay mineral is present in the soil, it is necessary to modify the minerals by chemical and thermal treatment. For this purpose, one of the 3 plates from each soil was heated to 500°C for 30 minutes. This causes collapse of any montmorillonite or vermiculite lattices present to a spacing of 9.5 Å to 10.5Å, which allows their indentification. A second plate from each soil was placed in a glycol atmosphere for 4 hours at a temperature of 50°C. Montmorillonite swells in glycol to a characteristic layer spacing of 17.7 Å and at this spacing produces a strong reflection hence montmorillonite can be distinguished from vermiculite.

Each plate was then placed in the X-ray machine and bombarded with X-rays while the plate was rotated through an angle of incidence from 2° to 30° at a rate of 1/2° per minute. The reflections were counted electronically and then recorded automatically on a graph showing the intensity of the reflection vs. the angle of incidence, as shown on plates 20 to 25 incl. in Appendix IV. The X-ray machine and electronic counter are shown in photograph 3.

The graphs obtained were analysed to determine the type and amount of clay minerals present. The Test Hole 140 soil is comprised of approximately equal amounts of illite and chlorite, a lesser amount of montmorillonite, and small amount of kaolonite. The Test Hole U of A soil is comprised of equal amounts of illite, kaolonite, and montmorillonite.

PHOTOGRAPH 3 - X-RAY DIFFRACTION EQUIPMENT

The approximate percentages of each mineral are reported in Table 4.

Because of the difficulty of determining the relative proportions of each

mineral when 3 or 4 clay minerals are present a range of percentages is

shown for each clay mineral.

8.5 Ion Exchange Capacity and the Exchangeable Cations

The methods used to determine the cation exchange capacity

are described in Appendices I and II. The shaking method of deter-

mining the ion exchange capacity (Appendix I) was used in the early part

of the testing programme. The apparatus used for this method is shown

in photographs 4 to 6 in Appendix I. However, the results obtained on

identical soil samples varied by as much as 100% with no apparent

reason. Later in the programme, this determination was carried out

on the same soils using the Alberta Soil Survey method (Appendix II) and

in this case the exchange capacity determinations on several samples of

identical soil agreed to within 5%. Furthermore, the Alberta Soil Survey

method gave an ion exchange capacity approximately half that of the

averageexchange capacity by the shaking method. For this reason, use of

the shaking method was discontinued and the results obtained by this

method are not reported. The ion exchange capacity determined on the

natural soils by the Alberta Soil Survey method is shown in Table 4.

The equipment used for this method is shown in photograph 7 to 9 in

Appendix II.

During the course of the investigation, it became mandatory to

know what cations were present in the natural soil and to what extent these had been replaced by other cations in the modified soils. The flame photometer method (Appendix II) and titration method (Appendix III) were used for these determinations.

The cations in the soil are comprised of two groups, viz. the adsorbed or exchangeable cations and cations in solution in the soil pore water. The cation exchange capacity is a determination of the total of adsorbed or exchangeable cations and does not include cations in solution. The quantitative determination of cations in the soil by the flame photometer and titration methods is for all cations present, both those adsorbed and those in solution. Where the sum of the individual cations determined by the preceding methods is within 5% of the cation exchange capacity, it can be assumed that there is an insignificant number of cations in solution. However, if the sum of the individual cations exceeds the exchange capacity, the cations in solution must be determined and then subtracted from the sum of the cations to give the exchangeable cations.

The cation exchange capacity and the percent of individual exchangeable cations for the natural soils from Test Hole 140 and U of A are reported in Table 4.

8.6 Atterberg Limits

The methods used for determination of the Atterberg Limits on the natural soil were identical with ASTM designations D 427-39, D 423-54 T, and D 424-54 T except that the soil was mixed to a slurry and vacuum

filtered to a moisture content near the liquid limit. The mixing and filtering required 3 days before testing. The limits and indices for the natural soils are shown in Table 4. The soils fall into the CH group on the Casagrande plasticity chart and are thus classified as inorganic clays of high plasticity.

8.7 Summary

The cation exchange capacity of these soils could be indicative of most any type or combination of clay minerals (Ref. Table I, section 2.10). With an exchange capacity near 25 me/100 gm. the soil could be an illite, an halloysite, an attapulgite, a chlorite, or a combination of any of these minerals plus montmorillonite and vermiculite. However, from general knowledge of the clay minerals of Alberta (section 2.8) it would be expected that the principal minerals are montmorillonite and illite. Furthermore there is unlikely to be a very large proportion of montmorillonite because of the relatively low cation exchange capacity.

The Atterberg limit tests demonstrate that the soil is highly plastic and has high liquid and plastic limits. These characteristics indicate the presence of the expanding lattice type of clay mineral, in this case suspected to be montmorillonite. A liquid limit of 80 indicates that the soil is not solely composed of the expanding lattice type of clay mineral or the liquid limit would be from 3 to 4 times greater.

The grain size analyses add weight to the evidence that montmorillonite is present because of the high (38-40) percent colloidal clay

sizes (< 0.2 micron) which generally contain montmorillonite. Further-
more the presence of 27-28% silt and sand sizes would suppress the cation
exchange capacity of an illite-montmorillonite clay.

Knowledge of the predominant clay minerals of Alberta, combined
with grain size analyses, cation exchange capacity determinations, and
Atterberg limit tests provide sufficient information to estimate that pro-
bably less than 50% of the clay minerals are montmorillonite and the re-
mainder are illite. The X-ray analysis shows this estimate to be partially
correct in that 1/5 to 1/3 of the clay minerals are montmorillonite. How-
ever illite, chlorite and kaolonite make up the remainder.

The relative abundance of the exchangeable cations in the natural
soil is Ca> Mg> Na = K. As discussed in section 5.1, this order of
abundance is typical of Alberta soils below the current zone of weathering.
the natural soil can therefore be considered a calcium soil.

CHAPTER 9

CONSOLIDATION TESTS

9.1 Purpose

The consolidation tests were conducted to investigate relative volume changes and the time-rate of volume change (as a function of the adsorbed cations) that a specimen undergoes when subjected to one-dimensional consolidation.

9.2 Procedures

Consolidation tests were conducted on remoulded Test Hole 140 soil and on remoulded and undisturbed Test Hole U of A soil. The remoulded samples were brought to a moisture content near the liquid limit using the procedure described in section 10.1, having previously soaked at higher moisture content for a period of 18 to 50 days. Both fixed ring and floating ring consolidometers with ring diameter of 2.60 in. and 3.00 ins. were used. The soil was spooned into the consolidometer in three lifts. The consolidation ring was placed on a glass plate and tapped briskly after each lift in order to reduce the air voids in the specimen. The top surface of the sample was then scraped flush with the top of the ring and the upper porous plate and loading head were placed in position. The consolidometer was quickly placed under the loading beam of a platform balance and an Ames dial was set in place to record deflection. The consolidometer tray was then filled with distilled water.

Seven increments of load were applied successively to the sample, ranging from 0.07 to 4.69 kg/cm^2. Each increment was allowed to act until primary compression was complete and the slope of the secondary compression branch was established. After establishing this slope for the final increment, the sample was allowed to rebound by removing three-quarters of the final load. When rebound was complete under the new load this procedure was repeated until the load was reduced to the original 0.07 kg/cm^2.

The testing procedure for remoulded natural soil from Test Hole 140 was modified in order to determine whether cations could be drawn into the soil in sufficient quantity during rebound to cause significant changes in the consolidation characteristics. For this purpose the soil was loaded in the manner described above, unloaded to 0.318 kg/cm^2 and then reloaded to 4.69 kg/cm^2 in order to establish the hysteresis loop of the natural soil. The water in the tray was then replaced by a solution of NaOH containing sufficient sodium to replace all the original cations. The sample was then allowed to rebound to 0.318 kg/cm^2 and take up sodium. It required 39 days for the sample to rebound under these conditions. The sample was then reloaded to 4.69 kg/cm^2, following which the load was removed in stages to the original load of 0.07 kg/cm^2.

Three undisturbed specimens were trimmed on a lathe to 2.60 in. diameter from 2.85 in. diameter samples. They were placed in the consolidometer, the Ames dials were set in place, the consolidometer trays

were filled with water, and nominal loads of 0.07 kg/cm^2 were applied.
When swelling under this load was complete, the load was increased
until the straight portion of the void ratio-log, pressure curve was estab-
lished. Hysteresis loops for the natural specimens were established in
the same manner as outlined previously. The distilled water in the three
trays was then replaced by solutions of KOH, MgO, and Ca(OH)$_2$ containing
sufficient of these cations to replace all the original cations respectively
and a second hysteresis loop was established in the same manner as des-
cribed above. Further load was then added to establish the slope of the
void ratio-log. pressure curve of the modified soil. The specimens were
then unloaded in stages to the original load of 0.07 kg/cm$_2$.

At the conclusion of the consolidation tests, the specimens were
weighed and then oven dried to determine the moisture contents and void
ratios. The cation exchange capacity and the type and amount of exchange-
able cations of each specimen was then determined in the manner described
in section 8.5.

9.3 Results of Cation Determinations

The cation exchange capacity and the proportion of individual
cations of the natural and modified soils are shown in Table 5. The values
reported are the average of two determinations. It will be noticed that
none of the modified soils are homionic. Nevertheless, in all but the Ca
modifications, a substantial increase in the desired cation has been prod-
uced by the medium of cation exchange.

The values reported for Test Hole 140 K and Mg modified soil
and the natural soil rebounded with NaOH are for total ions. Unfortunately

Soil	pH	Determination of Exchangeable Cations					Total Exchangeable Cations (me/100 gms)	Cation Exchange Capacity (me/100 gms)	Remarks
		% of Total Exchangeable Cations							
		Na	Ca	Mg	K	H			
Hole 140									
Natural	7.65	6	63	26	5	–	23.2	23.1	* Indicates percent of total cations present. There was insufficient of these modified soils to test for the proportion of cations in solution and therefore the percentages of exchangeable cations could not be calculated.
Na modification	10.72	18	66	11	5	–	29.2	29.1	
K modification	11.35	2*	28*	5*	65*	–	95.3#	26.6	
Mg modification	9.12	4*	42*	51*	3*	–	41.7#	23.6	
Not rebound with NaOH	7.65	31*	60*	7*	2*	–	55.9#	23.6	
Hole A of U Hole									# Indicates total cations which includes both exchangeable cations and cations in solution. Where the pH of the soil is above 7.5 there is no determination made for H ions as they will not be present in significant quantities.
Natural	7.52	7	65	21	7	–	25.1	26.3	
Na modification	12.1	65	27	3	5	–	32.2	31.7	
Ca modification	5.35	5	59	9	5	22	31.4	30.2	
Mg modification	7.28	4	20	62	6	8	30.1	29.1	
K modification	6.75	4	22	13	46	15	28.4	27.1	
H modification	3.30	6	21	14	3	56	26.1	29.3	
71' natural	7.52	5	64	26	5	–	28.3	27.2	
71' rebound with MgO	7.52	5	54	33	8	–	26.4	27.4	
73' natural	7.52	6	62	27	5	–	29.8	27.0	
73' rebound with KOH	7.52	5	49	12	34	–	26.8	26.2	
76' natural	7.52	6	68	22	4	–	29.2	25.0	
76' rebound with Ca(OH)2	7.52	5	67	22	6	–	24.3	29.6	

Table 5

Results of Cation Determinations

there was an insufficient quantity of these soils to determine the cations in the pore water so that the percentages of exchangeable cations could not be calculated. In the K modified soil 65% of the total cations were K; in the Mg modified soil 51% of the total cations were Mg; and in the natural soil rebounded with NaOH 31% of the total cations were Na. These percentages are considerably higher than those of the natural soil. Therefore it is logical to assume that a major portion of these additional K, Mg, and Na ions have become adsorbed.

The Na ion increased from 6% of the total exchangeable cations in the natural soil of Test Hole 140 to 16% in the Na modification. Since the Ca ion was the dominant exchangeable cation (66%) in the modified soil, it would be expected that the soil would exhibit the properties of a Ca soil. However, Winterkorn (1953) reports that the Na cation behaves differently from other cations in that it produces a marked effect on the soil properties when it accounts for only a small percentage of the total exchangeable cations. Tests on montmorillonite demonstrate that when as little as 15% of the exchangeable cations are Na, the soil behaves essentially as a Na soil.

Modification of the Test Hole U of A soil by means of cation exchange produced soils in which the added cations became the dominant adsorbed cations. In the Na modified soil 65% of the exchangeable cations were Na; in the Ca modification 59% were Ca; in the Mg modification 62% were Mg; in the K modification 46% were K; and in the H modification 56% were H ions. Except in the case of the Na modified soil, the presence of

extraneous cations in these modified soils is certain to have some neutral-
izing effect on the soil properties so that the observed differences in
properties of the modified soils will not be as pronounced as they would
have been had the modified soils been homionic.

Little or no change in the proportion of exchangeable cations was
observed in the three undisturbed consolidation test samples from Test
Hole U of A which were allowed to rebound in the presence of MgO, KOH,
and Ca (OH)$_2$. Mg increased from 26% to 33% of the exchangeable cations
in the sample from depth 71' which was rebounded in the presence of MgO;
K increased from 5% to 34% in the sample from depth 73' which was re-
bounded in the presence of KOH; and there was no significant change in the
proportion of Ca in the sample from 76' depth which was rebounded in the
presence of Ca(OH)$_2$. For this reason there is unlikely to be a noticeable
difference in the consolidation characteristics of the natural soil as com-
pared with the modified soil.

9.4 Effects of Exchangeable Cations on Pressure-Void Ratio Relationships

The experimentally obtained void ratio-log pressure curves are
shown in Plates 1 to 5 incl. The results for the consolidation tests are
given in Plates 26 to 44 inclusive in Appendix 4.

A comparison of compressive indices of the remoulded speci-
mens of the natural and modified soils (Plates 1 and 2) must be made on
the lower portion of the curves (1.0 to 4.69 kg/cm^2), the upper portions
of the curves being somewhat erratic because the specimens were not

VOID RATIO VS. LOG. OF PRESSURE

CONSOLIDATION TESTS ON REMOULDED
MODIFIED SOIL FROM TEST HOLE 140

PLATE I

PRESSURE [KG/CM²]

VOID RATIO VS. LOG. PRESSURE

CONSOLIDATION TESTS ON REMOULDED
NATURAL AND MODIFIED SOIL FROM TEST HOLE 3 OR X
AND

SOME SOIL SQUEEZED OUT OF RING DURING THIS INCREMENT

PRESSURE [KG/CM²]

PLATE 2

placed in the consolidometers exactly at the liquid limit. A comparison

of the slopes of the virgin branches of the e-log p curves shows that

there is no significant difference in the compressive indices of the natural

and modified soils.

The rebound portion of the curves of both Test Hole 140 and

Test Hole U of A remoulded soils show that when the pressure is reduced,

the Na modification undergoes a much greater increase in void ratio than

do the other soils. Table 6 gives the increase in void ratio during re-

bound of the natural and Ca, Mg, H, and K modified soils expressed as a

percentage of that of the Na modification. There is no significant differ-

ence in rebound of the natural and Ca, Mg, K and H modified soils.

Remoulded Soil	Increase in Void Ratio during Rebound (Expressed as a percentage of the Na modification rebound)	
	Test Hole 140	Test Hole U of A
Na modification	100	100
Ca ''	32	50
Mg ''	31	48
K ''	36	46
H ''	32	55
Natural	34	55
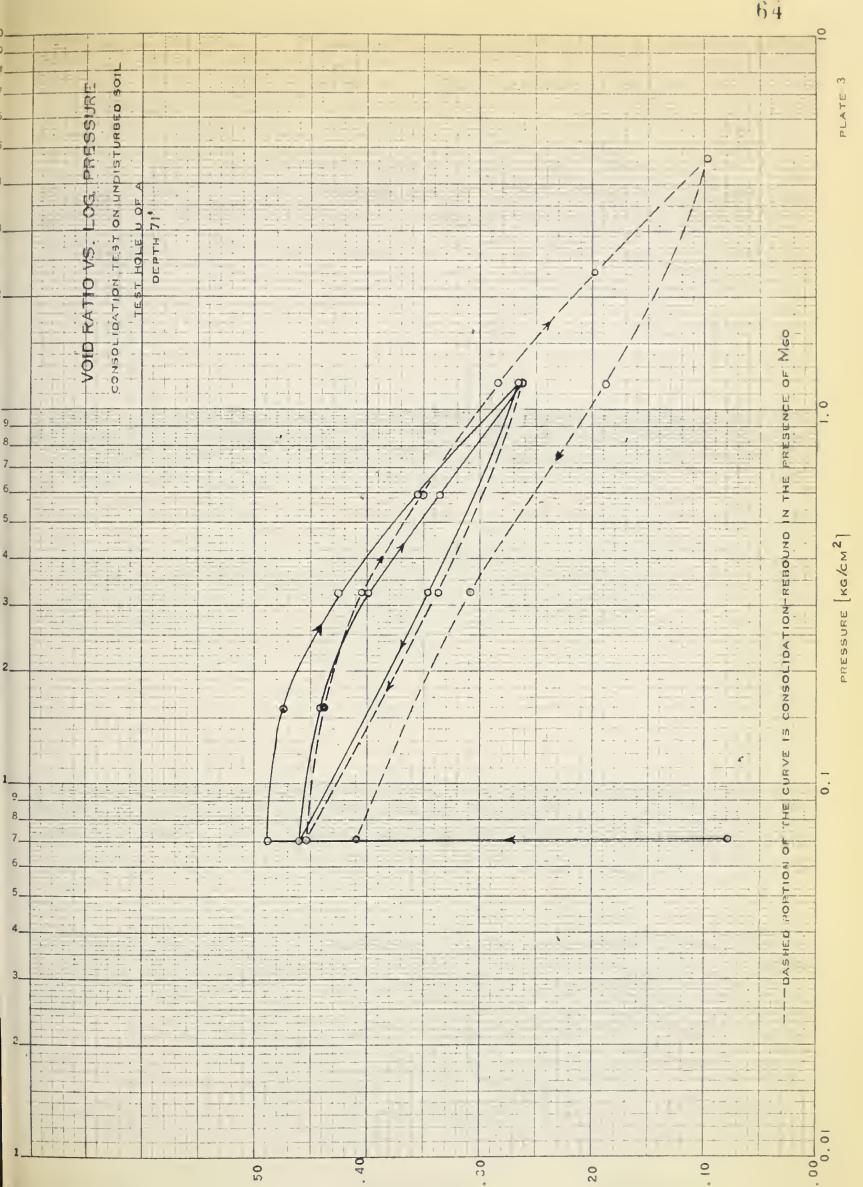
Table 6

Rebound of Remoulded Specimens of Natural and Modified Soils
Compared to that of the Na Modification
(Pressure decreased from 4.69 to 0.07 kg/cm^2)
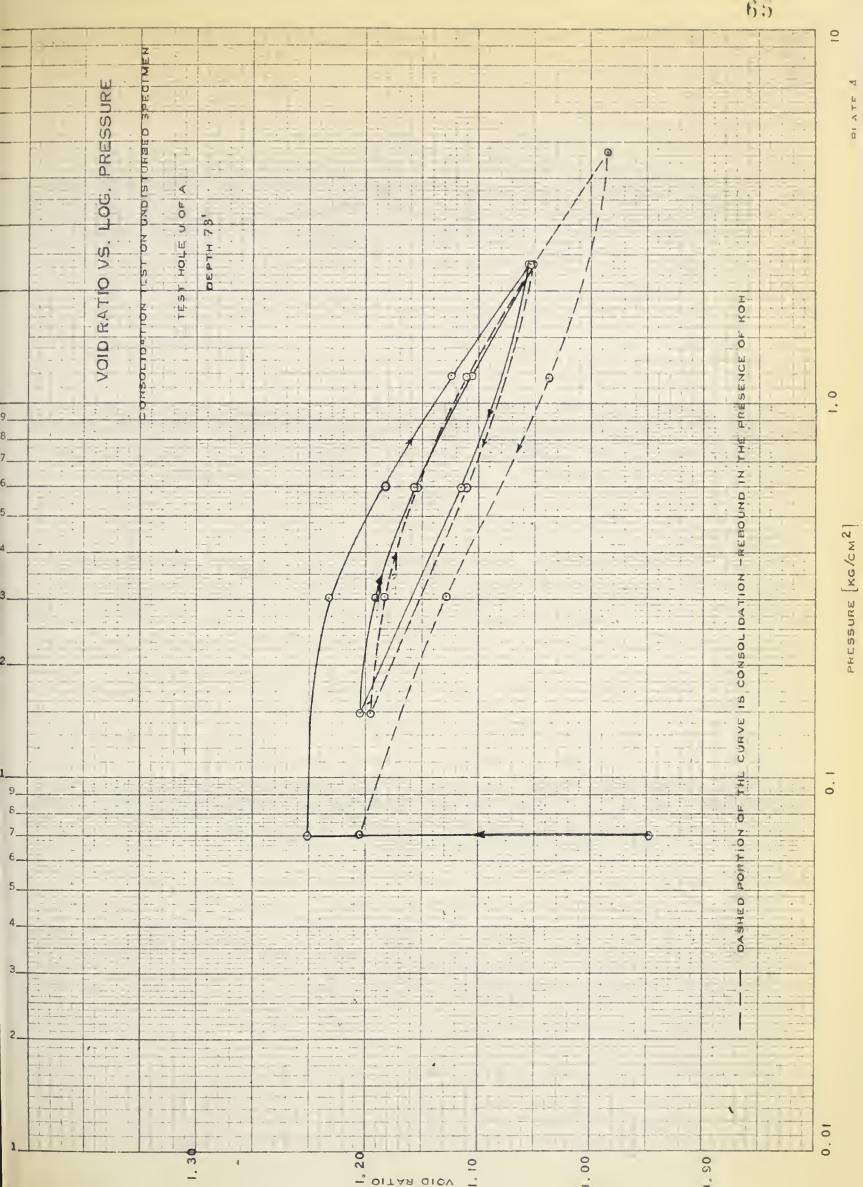
VOID RATIO VS. LOG. PRESSURE

CONSOLIDATION TEST ON UNDISTURBED SOIL

TEST HOLE U OF A

DEPTH 71'

PLATE 3

PRESSURE [KG/CM²]

— DASHED PORTION OF THE CURVE IS CONSOLIDATION-REBOUND IN THE PRESENCE OF MgO

VOID RATIO VS. LOG. PRESSURE

CONSOLIDATION TEST ON UNDISTURBED SPECIMEN

TEST HOLE U OF A.

DEPTH 78'

DASHED PORTION OF THE CURVE IS CONSOLIDATION —REBOUND IN THE PRESENCE OF KOH

—— DASHED PORTION OF THE CURVE IS CONSOLIDATION —REBOUND IN THE PRESENCE OF KOH

PRESSURE [KG/CM²]

VOID RATIO

VOID RATIO VS. LOG. PRESSURE

CONSOLIDATION TEST ON UNDISTURBED SPECIMEN

TEST HOLE U OF A

DEPTH 176'

PRESSURE [KG/CM²]

———— DASHED PORTION OF THE CURVE IS CONSOLIDATION REBOUND IN THE PRESENCE OF Ca[OH]₂

PLATE 5

The rebound of the Na modification is about three times the rebound of the others in the case of Test Hole 140 soil and about twice that of the others in the case of the Test Hole U of A soil.

The e-log p curves for the undisturbed samples from the U of A Test Hole (Plates 3, 4, and 5) show no significant change in the compressive indices of the modified soil from those of the natural soil. All curves show less volume increase for the second rebound than for the first rebound but it is doubtful whether the lesser volume increase can be attributed to changes in adsorbed cations as there is likely to be some particle re-arrangement during each compression.
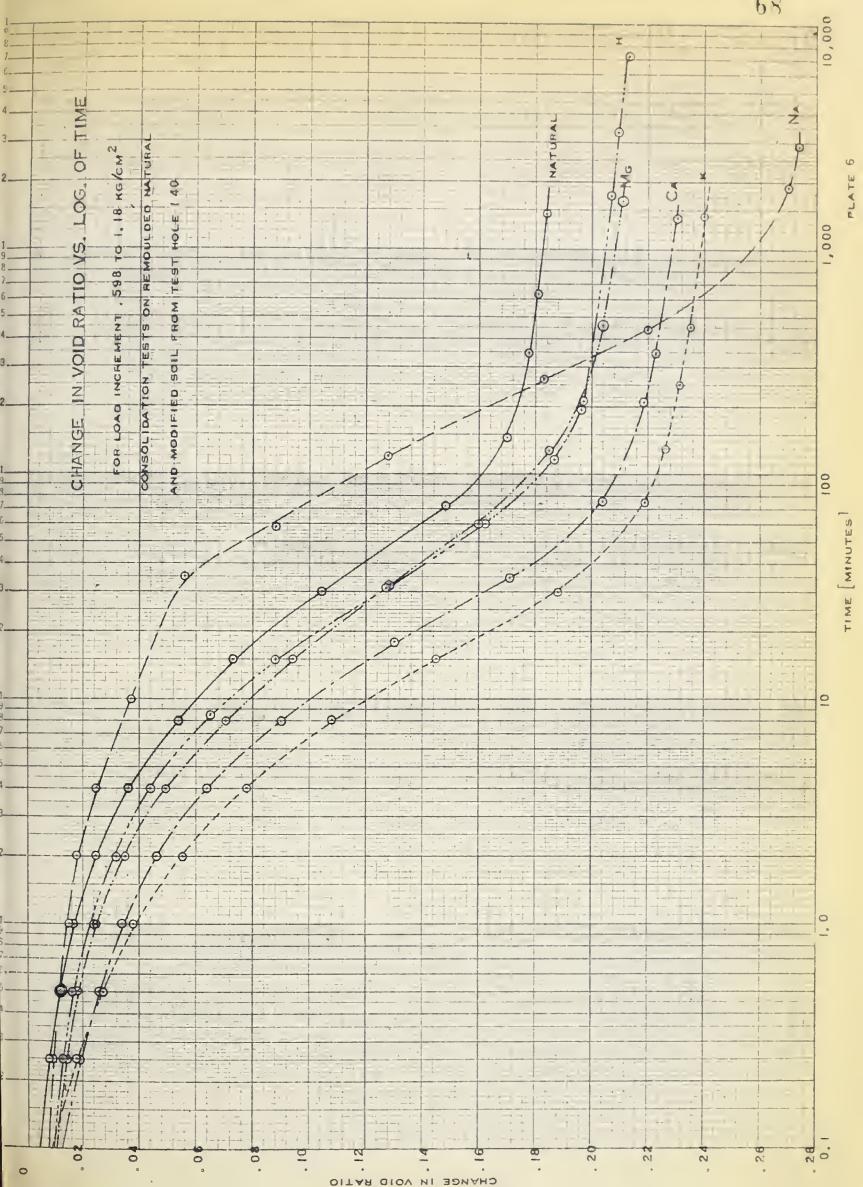
From the results of these tests it must be concluded that there was no significant difference in volume change during compression in any of the natural and modified soils tested. As to swelling characteristics, it is conclusive that Na soil, if unloaded in the presence of water, will attract a large amount of water in comparison with soils containing other cations.

9.5 Effects of Exchangeable Cations on the Rate of Volume Change
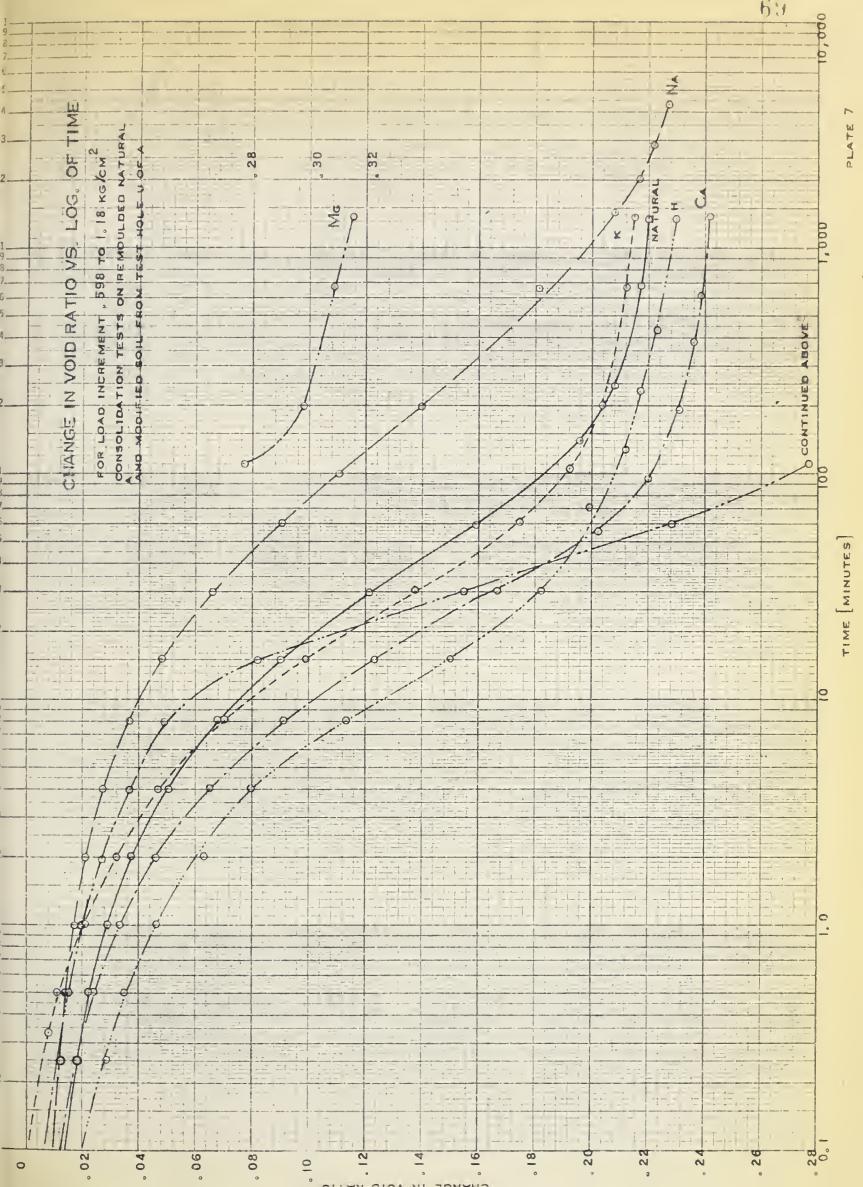
The consolidation-time curves for the 0.598 to 1.18 kg/cm^2 pressure increment of the consolidation tests are shown in Plates 6, 7, and 8. The coefficient of permeability of the various soils for this pressure range was calculated as outlined below. From the consolidation-time curves the coefficient of consolidation, c_v, was obtained by use of the equation:

$$c_v = \frac{0.197(H)^2}{t_{50}} \quad (cm^2/sec)$$

CHANGE IN VOID RATIO VS. LOG. OF TIME

FOR LOAD INCREMENT .598 TO 1.18 KG/CM²

CONSOLIDATION TESTS ON REMOULDED NATURAL
AND MODIFIED SOIL FROM TEST HOLE I 40

PLATE 6

TIME [MINUTES]

CHANGE IN VOID RATIO

CHANGE IN VOID RATIO VS. LOG₀ OF TIME

FOR LOAD INCREMENT .598 TO 1.18 KG/CM²
CONSOLIDATION TESTS ON REMOULDED NATURAL
AND MODIFIED SOIL FROM TEST HOLE U OF A

PLATE 7

CHANGE IN VOID RATIO VS. LOG OF TIME

FOR LOAD INCREMENT 0.598 TO 1.18 KG/CM².

CONSOLIDATION TESTS ON UNDISTURBED SPECIMENS

78' KOH
76' NATURAL
76' CA(OH)₂

73' NATURAL

71' MGO

71' NATURAL

TIME [MINUTES]

NATURAL SOILS

SAME SOILS AFTER REBOUND IN THE PRESENCE OF REAGENTS

where H = one-half of the reduced height of the specimen (cms)
t_{50} = time in seconds at which 50% of the theoretical consolidation is attained.

The coefficient of compressibility, a_v, was obtained by use of the equation:

$$av = \frac{0.435\ C_c}{p} \quad (cm^2/gm)$$

where C_c = the slope of the e-log p curve over the pressure range 0.598 kg/cm^2 to 1.18 kg/cm^2.
p = average pressure for the increment.

The coefficient of permeability, k, was calculated from the equation:

$$k = \frac{C_v\ a_v\ w}{1 + e} \quad (cm/sec)$$

where c_v and a_v are as defined above.
w = unit weight of pore fluid (gm/cm^3) (assumed equal to 1 for these calculations).
e = average void ratio for the increment.

The k values of the various soils for the 0.598 to 1.18 kg/cm^2 pressure range are given in Table 7. The average permeability of the remoulded Test Hole 140 and U of A soils increases in the order Na <

Natural < Mg = H < Ca < K. The remoulded Na soils are in the order of 7 times less permeable than the natural soils and the remoulded K and and Ca soils are approximately twice as permeable as the natural soils. The permeability of the undisturbed specimens from 76' depth is approximately the same before and after rebounding with Ca(OH)$_2$. This was to be expected because the cation determinations showed no significant

Soil	k (cm/sec x 10^{-8})		
	Test Hole 140	Test Hole U of A	Average
Remoulded Natural	1.6	1.5	1.6
" K	4.6	2.9	3.8
" Ca	3.1	3.5	3.3
" Mg	2.6	2.4	2.5
" H	2.2	2.8	2.5
" Na	0.39	0.27	0.33
Undisturbed 71' Natural	-	0.19	-
" 71' Rebound with MgO	-	0.29	-
" 73' Natural	-	0.24	-
" 73' Rebound with KOH	-	0.23	-
" 76' Natural	-	0.18	-
" 76' Rebound with Ca(OH)$_2$	-	0.21	-

Table 7

Coefficient of Permeability of Natural and Modified Soils
for Pressure Range 0.598 to 1.18 kg/cm^2

difference in the proportion of ions present in the natural soil and that

rebounded with Ca(OH)$_2$.   There was an increase in permeability of the

undisturbed sample from 71' depth after rebounding in the presence of

MgO.   This increase is a logical result of the increase in the proportion

of Mg and K ions which occurred in this specimen.   The permeability of

the specimen from 73' depth remained the same after rebounding with

KOH.   This is not what might be expected since the cation determinations

(Table 5) show that the proportion of adsorbed K ions was markedly in-

creased by rebounding the soil in the presence of KOH.   A possible

explanation is that in this specimen a structural collapse occurred at

higher pressures during the first loading thus counteracting any increase in permeability occasioned by an increase in K ions.

It can be concluded from these results that by replacing the original cations on these clay shales with K or Ca, the permeability may be at least doubled and by replacing the original cations by Na, the permeability may be reduced at least seven times.

CHAPTER 10

PLASTICITY AND SHRINKAGE DETERMINATIONS

10.1 Procedures

Atterberg limit tests were conducted as described in ASTM designations D 427-39, D 423-54T, and D 424-54 T except for the manner in which the soil was prepared. The modified soils from Test Hole 140 were mixed into a slurry with a reagent containing the desired cation and then placed in metal containers, stirred occasionally, and allowed to dry until the moisture content approached the liquid limit. Samples were then taken from the containers for testing, some 11 to 22 days after mixing with the cations.

It became apparent at about the 15th day of storing in the tin containers that there was a chemical reaction occurring between the soil solution and the tin. For this reason the modified soils from Test Hole U of A, which were prepared some time later, were stored in glass containers. At this stage in the testing programme it was suggested that complete cation exchange might not be occurring immediately after mixing. It was therefore recommended that liquid and plastic limit tests be run on each modified soil over a period of time, to establish if there was any change in plasticity with time. If the liquid and plastic limits remained constant with time it could be assumed that there was no cation exchange taking place. It was also decided to speed up the exchange reaction, should it be slow, by making the ions in solution more accessible to the
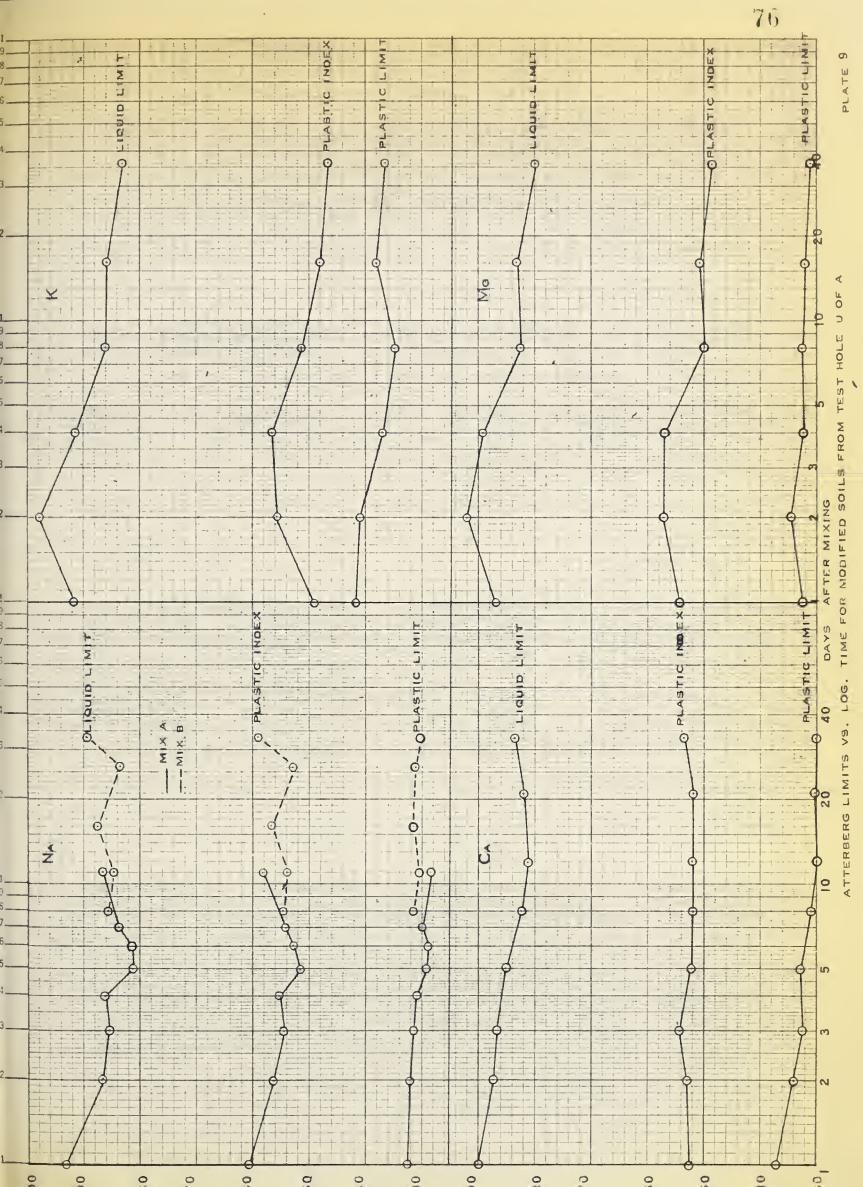
exchangeable ions.

Consequently the soil from the U of A test hole was mixed into a slurry with a reagent containing the desired cation and was then stored in air tight glass containers in this liquid condition. The containers were shaken well each day to ensure maximum contact of solution with soil. At time intervals of 1, 2, 4, 8, etc., days after mixing, samples were poured into a vacuum filter and the soil moisture content was reduced to near the liquid limit in 4 to 6 hours. Liquid and plastic limits were then run on the samples, further drying being accomplished by passing air over the samples.

The shrinkage limits were run only once on each sample, 20 to 25 days after mixing, as it was felt that the shrinkage limit would be relatively insensitive to any cation exchange that should occur after that length of time.

10.2 Time Influence on Plasticity Characteristics

Plate 9 gives the results of liquid and plastic limit tests run on the U of A soil modifications over a period of 1 to 36 days after mixing with the desired cation. The liquid limit of the Na modification fluctuates erratically with time, indicating that cations were continually being exchanged between the soil and the soil solution. The plastic limit, being less sensitive to changes in cations, fluctuated little. The plastic index reflects the continuous change in the liquid limit. The liquid limit of the Ca modification changed uniformly with time, gradually decreasing during

ATTERBERG LIMITS VS. LOG. TIME FOR MODIFIED SOILS FROM TEST HOLE U OF A

PLATE 9

the first 12 days and then slowly increasing. The plastic limit of this

soil declined considerably during the first 3 days, then more slowly up to

12 days where it levelled off. The plastic index remained essentially con-

stant the entire time. The liquid limits of both the K and Mg modifications

increased during the second day then decreased considerably during the

next eight days, after which time they changed little. The plastic limit

of the K modification dropped gradually for 8 days and then increased

slightly thereafter. The plastic limit of the Mg modification changed little

with time. The plastic index of both K and Mg soils rose considerably

during the second day and then gradually fell, levelling off at about 16

days after mixing.

It can be inferred from the above results that with the exception

of the Na soil, the cation exchange was essentially complete 16 days after

mixing of these modified soils.

10.3 Plasticity and Shrinkage Characteristics of the Modified Soils
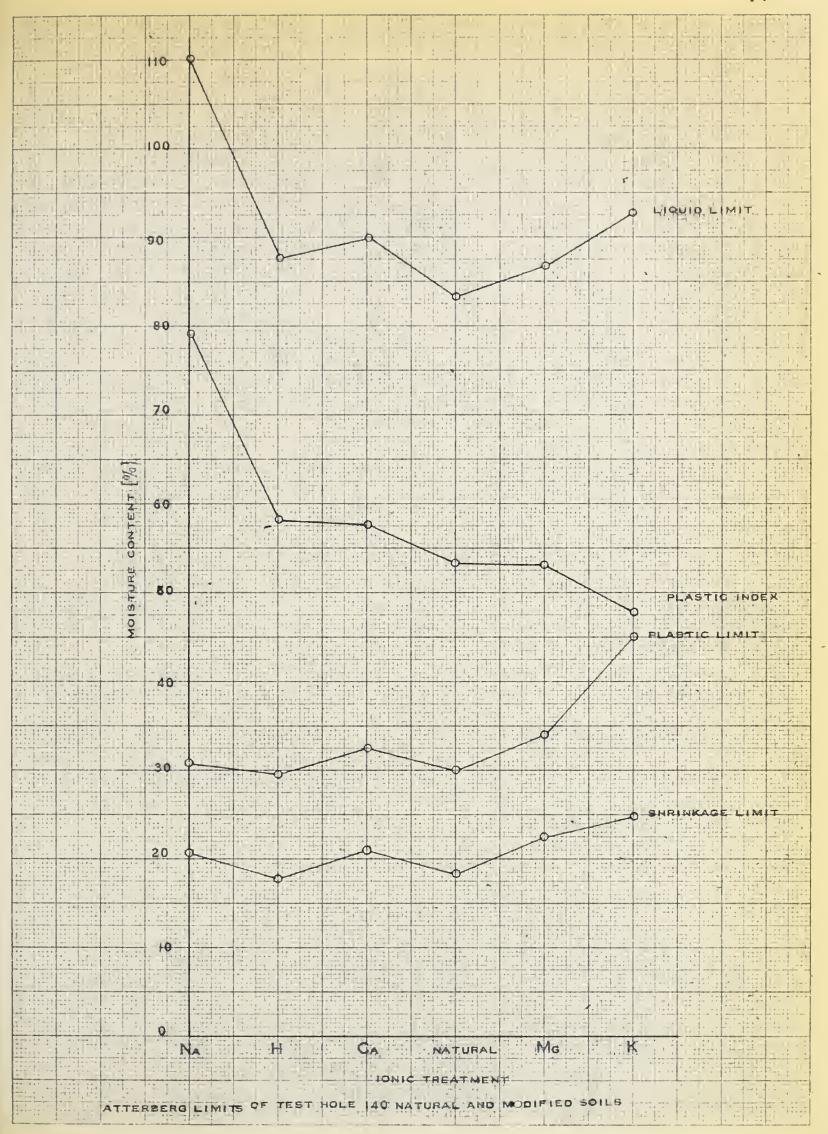
Table 8 and Plates 10 and 11 give the results of the liquid, plastic,

and shrinkage limit determinations on the natural and modified soils. The

liquid and plastic limits of the natural soil were determined 3 days after

the soil was first mixed into a slurry. Those of the H modification were

determined 10 days after mixing with HCl. The values reported for the

other modifications of Test Hole 140 soils were determined from 11 to 22

days after preparation of the soils. The values reported for the Na, Ca,

K and Mg modified Test Hole U of A soils were determined 33 to 36 days

after preparation of the soils.

Soil	Test Hole 140 (75' – 115')					Test Hole U of A (68' – 76')				
	W_l	W_p	W_s	I_p	Shrinkage Ratio	W_l	W_p	W_s	I_p	Shrinkage Ratio
Natural	83.2	29.9	18.4	53.3	1.72	81.7	30.4	16.6	51.3	1.79
Hydrogen Modification	87.8	29.6	17.9	58.2	1.83	86.6	31.7	20.2	54.9	1.71
Sodium Modification	110.3	30.9	20.8	79.4	1.72	89.3	30.3	18.5	59.0	1.79
Potassium Modification	92.6	45.0	24.7	47.6	1.60	83.7	36.7	24.5	47.0	1.61
Calcium Modification	90.0	32.4	21.0	57.6	1.68	83.9	30.0	21.9	53.9	1.68
Magnesium Modification	86.8	33.8	22.5	53.0	1.65	80.1	31.3	22.1	48.8	1.66
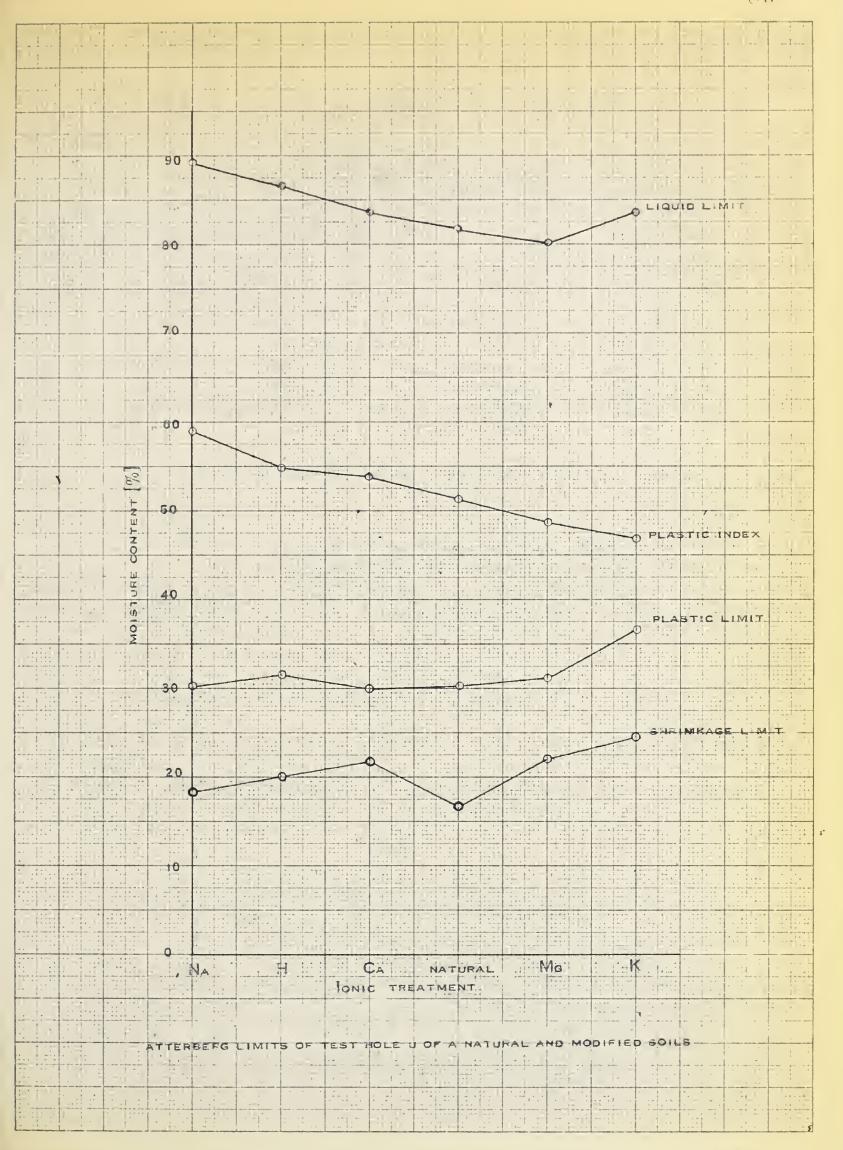
Table 8

Results of Atterberg Limit Tests

ATTERBERG LIMITS OF TEST HOLE 140 NATURAL AND MODIFIED SOILS

PLATE 10

ATTERBERG LIMITS OF TEST HOLE J OF A NATURAL AND MODIFIED SOILS

The range of values of the Atterberg constants for the various soils are as follows:

	Hole 140 Soils	Hole U of A Soils
liquid limit	83.2 to 110.3	80.1 to 89.3
plastic limit	29.6 to 45.0	30.0 to 36.7
plasticity index	47.6 to 79.4	47.0 to 59.0
shrinkage limit	17.9 to 24.7	16.6 to 24.5
shrinkage ratio	1.60 to 1.83	1.61 to 1.79

The relative values of these constants are given in Table 9:

Constant	Relative Values of the Atterberg Constants	
	Hole 140 Soils	Hole U of A Soils
Liquid limit	Na>K>Ca>H = Mg>Natural	Na>H>K = Ca>Mg>Natural
Plastic limit	K>Mg>Ca>Na = Natural = H	K>H = Mg>Natural = Na = Ca
Plasticity Index	Na>H = Ca>Natural = Mg>K	Na>H = Ca>Natural>Mg>K
Shrinkage limit	K>Mg>Ca = Na>Natural = H	K>Mg = Ca>H>Na>Natural
Shrinkage ratio	H>Natural = Na>Ca>Mg>K	Natural = Na>H>Ca>Mg>K

Table 9

Relative Values of the Atterberg Constants for the Modified Soils

The most striking results of this series of tests are the substantial increases of the liquid limit of the Na modifications and of the plastic limit of the K modifications. The net result is that the Na soils have the highest plastic index and the K soils have the lowest plastic

index.   The Na soils also show the greatest difference in moisture con-

tent between the liquid limit and the shrinkage limit, while the Mg clays

show the smallest.

CHAPTER 11

CONCLUSIONS AND RECOMMENDATIONS

11.1 The Significance of the Test Results

The effects of the exchangeable cations as evidenced in the results of the tests conducted for this investigation are somewhat masked by the presence of extraneous cations in all but the Na modified soils. In the Na modified soils at least 15% of the exchangeable cations were Na, which, according to Winterkorn (1953), is sufficient to cause the soil to behave as a homionic Na soil. The results of tests on the other modified soils represent the effects of a soil which has one dominant cation and lesser quantities of other exchangeable cations. Therefore the effects observed in the Ca, Mg, K, and H modified soils may or may not be of the same magnitude as those which would be observed in homionic soils. However they are believed to be generally indicative of the trends which would be produced in homionic soils. The results serve a useful purpose by representing the conditions which would occur in a soil in the field which is in a transitional state between a multionic soil and a homionic soil and which has one dominant exchangeable cation.

In order to determine the basic effects of the various cations, further laboratory investigations of this type should be confined to homionic soils because it is impossible to estimate the degree of magnifying or suppressing effects of extraneous cations in soils which are not homionic.

11.2 Conclusions

First

The work which is presented in this thesis has been performed to indicate some of the relationships of the type of exchangeable cations with the engineering properties of a Northern Alberta clay shale. Although homionic soils must be prepared and tested in a similar manner before final conclusions can be reached, certain noteworthy trends have been demonstrated. The following effects of the different ions were observed:

(1) The Na ion caused the highest increase in the plasticity· index of the soil by markedly increasing the liquid limit. It caused the greatest difference in moisture content between the liquid limit and the shrinkage limit. It caused two to three times as much swelling of the soil as did the other exchangeable cations. The Na modified soil was approximately seven times less permeable than the natural soil.

(2) The H ion increased the plasticity index of the soil by increasing the liquid limit. The H modified soil was slightly more permeable than the natural soil.

(3) The Mg ion decreased the plasticity index of the soil by increasing the plastic limit. It caused the least difference in moisture content between the liquid limit and shrinkage limit. Both the remoulded and undisturbed Mg modified soils were slightly more permeable than the natural soils.

(4) The Ca ion increased the plasticity index of the soil by increasing the liquid limit. The Ca modified soils were about twice as

permeable as the natural soils.

(6) The K ion caused the most reduction in the plastic index by increasing the liquid limit and markedly increasing the plastic limit. The remoulded K soil was the most permeable of all soils tested, having a permeability more than double that of the natural soil.

Second

It follows from these observations that to decrease the permeability of these clay shales, for example if they are to be used for canal linings, the original cations could be replaced by Na. Where it is desirous to increase the permeability of these shales and to decrease shrinkage and swelling, if for example this soil is to be used as a foundation material, the original adsorbed cations could be replaced by K.

Third

The effects of the exchangeable cations observed in this investigation are not identical with those of Winterkorn and Moorman (1941) on tests of a beidellite clay of glacial and loessial origin (reported in Chapter 6). Both series of tests indicate that the Na ion produces a disperse structure and the K ion produces a flocculent structure. In both soils the Na ion caused the highest liquid limit, plasticity index, and lowest permeability and the K ion caused the highest plastic limit, the lowest plasticity index, and the highest permeability. However, in the beidellite soil the H ion appeared to act as a flocculating agent in that it caused almost as high permeability as the K ion and a low plasticity index, whereas

in the Northern Alberta clay the H ion caused almost as high a plasticity index as the Na ion and relatively low permeability. The effects of the Ca and Mg ions were similar in both series of tests.

Fourth

The increase in permeability and increase in shrinkage limit caused by the K, Ca, and Mg ions are evidence of the flocculent structure. Since shrinkage of clays occurs by diminution of volume as a result of (1) decreasing the amount of water in the interlayers of expanding lattice minerals and (2) increasing compressive stresses originating in capillary forces as water evaporates, it follows that those cations which cause aggregation of clay minerals will shrink least because pore size will be larger, hence capillary tension will be less. Conversly, the evidence of a non-aggregating or dispersed soil structure is a lower shrinkage limit and a lower permeability such as exhibited by the Na and H modified soils.

Fifth

It is important to note that for homionic variations of a given soil, it appears that the degree of flocculation is indicated by the plasticity index. The flocculent soils have lower plasticity indices and the dispersed soils have higher plasticity indices.

Sixth

It is postulated that a divalent ion causes a flocculent structure by sharing its charges between two soil particles thus creating aggregates

and relatively large voids. The monovalent ions are unable to do this because they have only one charge. If this theory is correct, the K ion should not have produced a flocculent structure. However, the K ion did produce a flocculent structure in both the beidellite soil tested by Winterkorn and Moorman and in the clay shales investigated in this programme. It is therefore apparent that the K ion has a binding effect on the clay lattice that is not explanable entirely in terms of the charge on the ion.

Seventh

It was observed that there was fluctuation in liquid and plastic limits of the modified soils over a considerable period of time after mixing the soil with the reagents. The changing limits are believed to be indicative of continuing cation exchange between the soil and the solution. In the case of the Mg, K and Ca modifications, the liquid and plastic limits showed no significant change after 16 days, thus indicating that there was little cation exchange after this time. The liquid limit of the Na modification had not become constant 33 days after mixing the soil with NaOH, indicating that cations were still being exchanged between the soil and solution.

Complete replacement of the original cations was not achieved in any of the modified soils. This result is in accordance with the statement by Wilklander (1955) that the exchange reaction is subject to the principle of chemical equilibrium. The cations brought into solution by exchange must be removed from contact with the soil; otherwise the replacement will not be complete. Leaching the soil with the desired

reagent until the reagent comes through unchanged appears to be the best method of producing homionic soils.

Eighth

It can be concluded that cation exchange is a slow reaction, requiring several days to reach equilibrium, if the original adsorbed cations are not completely removed from the system and if the soil to solution ratio is greater than 1:2. Gedroiz, cited by Kelley (1948), found that in shaking 50 grams of soil and 500 cc of 1 N NH_4Cl (soil to solution ratio 1:10) that the equilibrium was established by shaking only 3 minutes. Extrapolation of these results would indicate that deliberate cation exchange of natural soils in place would be a slow process, requiring perhaps months or years, because of the high soil to solution ratio. In addition, the characteristically low permeability of clays would result in slow diffusion of cations into the soil mass, causing even slower cation exchange.

11.3 Summary

The trends established in this investigation may be summarized as follows:

(1) The plasticity characteristics of the clay shales of Northern Alberta can be substantially modified by changes of adsorbed cations.

(2) The permeability of remoulded clay shales can be significantly altered through the medium of cation exchange.

(3) Atterberg limit tests, conducted on homionic variations of a given soil, furnish evidence of the type of soil structure - flocculent

or disperse - caused by the various ions and can therefore be used for predicting in general terms, the effects of the ions on shrinkage, swelling, and permeability of that soil.

(4) Homionic soils can not be produced unless the ions which are being replaced are completely removed from contact with the soil. Leaching the soil with a reagent containing the desired cation is believed to be the best method of affecting complete cation exchange.

(5) The cation exchange reaction is slow, requiring several days to reach equilibrium, if the soil - solution ratio is 1:2 and if the original cations are not removed from the soil - solution system.

11.4 Recommendations for Further Research

On the basis of the results of this investigation it is recommended:

(1) That similar tests be conducted on homionic clay shales from Northern Alberta to establish the effect of each cation on plasticity, shrinkage, swelling, permeability, and consolidation characteristics.

(2) That homionic soils for similar investigations be produced by leaching the natural soil with a reagent containing the desired cation rather than mixing the soil and reagent. The homionic soils should then be leached with distilled water to remove any ions from solution. The leaching process can be speeded up by forcing the leachate through under pressure rather than sucking it through under a vacuum.

(3) That further tests be conducted to determine what proportion

of the total exchangeable cations must be Ca, Mg, H, or K cations in order to produce substantially the same effects as homionic soils.

(4) That an investigation be conducted to determine the effect of changes in the concentration of ions in the pore fluid on the swelling and swelling pressures of homionic soils.

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APPENDIX I

Shaking Method Used for Measuring Cation Exchange Capacity

This method is similar to one used by D. T. Davidson and John B. Sheeber outlined in Symposium on Exchange Phenomena in Soils, ASTM, 1952. The procedures used in measuring the cation exchange capacity of a sample are presented in the following order: exchange of cations, distillation, titration, and calculations.

1. Exchange of Cations

Approximately ten grams of air dry soil ground to pass the No. 40 sieve is accurately weighed to 0.001 gm and placed in a rubber stoppered bottle and shaken by hand with 250 ml of ammonium acetate solution. The ammonium acetate solution is a neutral 1 normal solution. The pH of the normal solution may be adjusted to pH 7.0 by the use of either ammonium hydroxide or acetic acid, depending on the initial pH. The soil is then allowed to settle and the clear supernatant liquid above soil is suction-filtered through a funnel fitted with a dense filter paper. The bottle is then refilled with 250 ml of fresh ammonium acetate solution. After the shaking and settling operation has been repeated, the supernatant liquid is filtered through the funnel and the soil washed into the funnel and filtered. The soil is then washed with 150 ml of neutral 70 per cent methyl alcohol solution prior to determining the amount of ammonium ions adsorbed on the soil. The apparatus for filtering the soil is shown in photograph 4.

PHOTOGRAPH 4 - FILTERING APPARATUS FOR CATION EXCHANGE CAPACITY DETERMINATION

2. Distillation

Immediately following the alcohol washing the sample containing ammonium that has been taken up by exchange is transferred to a 500 ml Kjeldahl flask and covered with 150 ml of distilled water. The transfer of soil from the funnel is best accomplished by rolling up the sample in the filter paper and transferring paper and sample to the Kjeldahl flask. Wetting the caked soil slightly facilitates this operation. Soil grains clinging to the sides of the funnel may be transferred by wetting a clean sheet of filter paper with distilled water and wiping the inside of the funnel clean: the filter paper is then placed in the flask.

Next measure exactly 50 ml of 0.1000 N hydrochloric acid and place in a 500 ml Erlenmeyer flask. Place the flask under the condenser with the receiving tube of the condenser extending well into the acid. Add 1 ml of 0.2 per cent methyl red solution to the acid and a full teaspoon of magnesium oxide to the contents of the Kjeldahl flask. Check all connections of the distillation apparatus to make sure they are tight enough to prevent any escape of ammonia. Then light the burner under the Kjeldahl flask and distill the contents nearly to dryness. The distillation apparatus is shown in photograph 5.

Care should be exercised throughout the distillation to prevent acid from being sucked up into the Kjeldahl flask. Should the acid start to be sucked up into the condenser, the connecting line at the top of the condenser should be momentarily opened. Make sure that the flame is on throughout the distillation as a loss of heat source will create a

PHOTOGRAPH 5

DISTILLATION APPARATUS FOR CATION EXCHANGE CAPACITY DETERMINATION

vacuum in the distillation system and suck acid up into the condenser. At the end of the distillation, disconnect the Kjeldahl connecting bulb before removing the flame.

3. Titration

Remove the Erlenmeyer flask and wash the acid off the receiving tube into the flash with distilled water. Titrate the excess acid with 0.1000 normal sodium hydroxide, reading the burette to the nearest 0.1 ml. The end-point of the titration occurs at a pH of exactly 6.20. The end-point can be determined most accurately by the use of a pH meter, but if no pH meter is available, the end-point is evidenced by a yellow-orange color. At a pH of about 5.7, the color turns from red, to red-orange and then fades to yellow-orange as the titration proceeds to pH 6.20; there is a difference of 0.5 to 0.7 ml between pH 5.7 and 6.20. The titration apparatus is shown in photograph 6.

4. Calculations

The cation exchange capacity of the sample may now be calculated in milliequivalents per 100 g of oven-dry soil.

The oven-dry weight of the sample used is determined by correcting the air-dry weight for hygroscopic moisture as follows:

$$d = a \frac{100}{100 + p} \qquad (1)$$
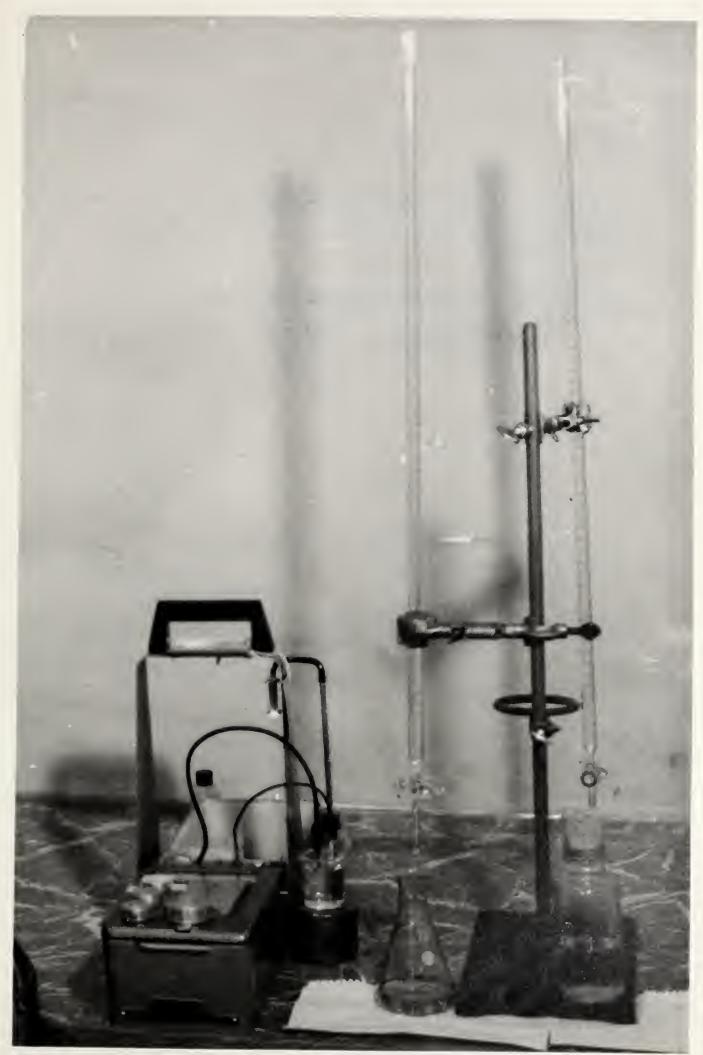
where: $d =$ wt of oven-dry sample in grams
$a =$ wt of air-dry sample in grams
$p =$ percent hygroscopic moisture.

PHOTOGRAPH 6

TITRATION APPARATUS FOR CATION EXCHANGE CAPACITY DETERMINATION

The cation exchange capacity is calculated from the following equation:

$$c = \frac{A - B}{d} \times 100 \qquad (2)$$

where: c = cation exchange capacity in m.e. per 100 g
A = (ml of HCl used) (normality of HCl)
B = (ml of NaOH used) (Normality of NaOH)
d = wt of oven-dry sample in grams.

In general, cation exchange capacity values should be reported as the average of at least two determinations.

APPENDIX II

Cation Exchange Capacity and Determination of Exchangeable Cations -
Mg, Ca, Na, K

(Alberta Soil Survey Procedure)

Reagents: 1 N Ammonium acetate adjusted to pH 7

95 per cent ethyl alcohol

1 N NaCl solution

1. Leaching and Total Exchange Capacity

   a. Weigh 10 gm of soil (less if high in organic matter) and place

      in 100 ml. plastic contrifuge tubes.

   b. Add approximately one teaspoonful of ground filter paper to each

      tube.

   c. Add 40 ml of 1 N NH_4Ac, stopper the tubes shake for five minutes,

      and allow to stand overnight.

   d. Shake again for 15 minutes. Prepare Buchner funnels and suction

      flasks with filter paper and a coating of celite as shown in photo-

      graph 7.

   e. Transfer contents of centrifuge tube to Buchner funnels with as-

      piration applied. Rinse tubes and stoppers with wash bottle of

      1 N NH_4Ac.

   f. Wash the soils in the funnels with four successive 40 ml portions

      of 1 N NH_4Ac with aspiration between each washing.

   g. Transfer the NH_4 Ac leachate in suction flasks to 250 ml

PHOTOGRAPH 7 - ALBERTA SOIL SURVEY FILTRATION APPARATUS

volumetrics (rinse flasks with 1 N NH_4Ac) and make to volume.
Save 75-100 ml of the leachate for Ca, Mg, Na, and K deter-
mination on the flame photometer.

h. Replace the Buchner funnels containing the NH_4 saturated soil to
the corresponding suction flask and wash with five successive 40
ml portions of 95% ethyl alcohol, applying aspiration to dryness
between each washing. This removes any free NH_4Ac. Discard
the washings and rinse flasks 3-4 times with water, the last of
which is distilled water.

j. Leach the soils with four separate 50 ml portions of 1 N NaCl,
applying aspiration between each leaching. Make NaCl leachate
to a final volume of 250 ml in volumetrics using distilled water.

k. Determine their ammonia content by distilling as outlined below.
Use a 100 ml aliquot plus 5 gms magnesium oxide, a few grains
of zinc, small amount of paraffin, and 200 ml of cold tap water.
The distillation apparatus is shown in photograph 8.

l. Ammonia is recovered in 4 per cent boric acid solution. Ammonia
is determined by titrating with standardized H_2SO_4 using 3 drops
of Bromocresol Green and 5 drops methyl red indicator.

m. Total Exchange Capacity $= \dfrac{\text{ml } H_2SO_4 \times \text{normality}}{\text{sample weight}} \times \dfrac{250}{100} \times 100$

2. Determination of Exchangeable Mg, Ca, Na, and K in 1 N NH_4Ac Solution

Using the Flame Photometer
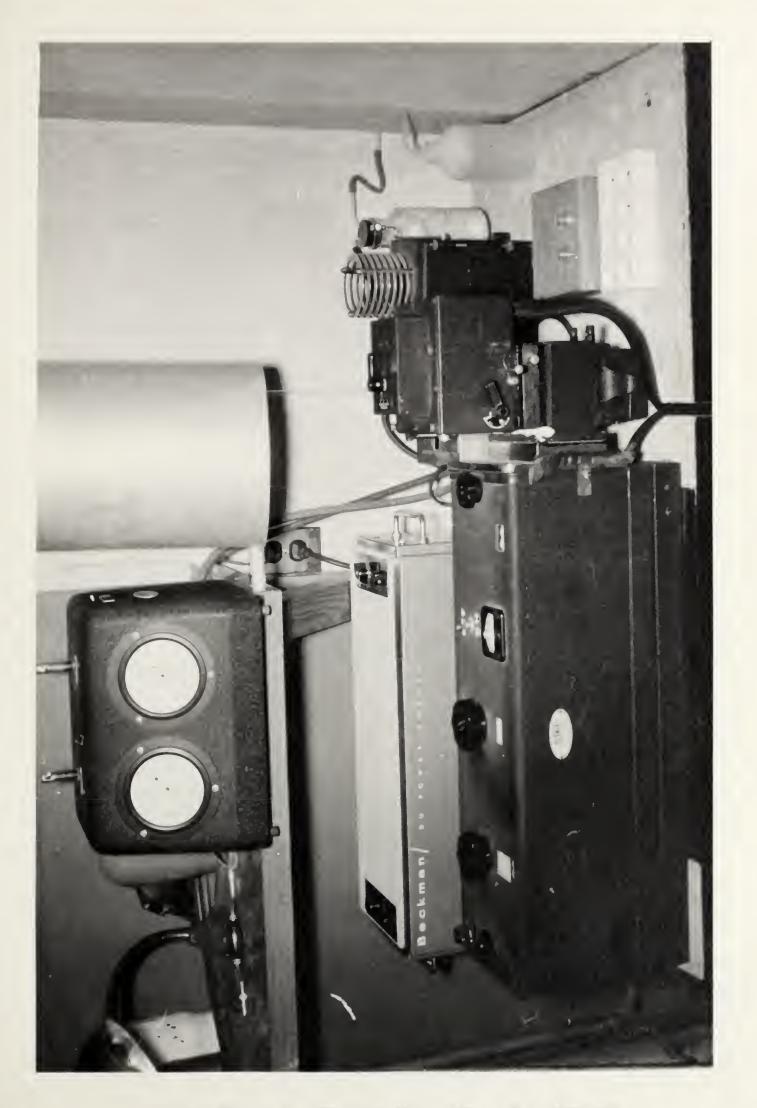
Equipment: Model DU Beckman Flame Photometer with
acetylene and oxygen burner (Shown in photograph 9).
Model 9200 photomultiplier

PHOTOGRAPH 8 - ALBERTA SOIL SURVEY DISTILLATION APPARATUS

PHOTOGRAPH 9 - BECKMAN FLAME PHOTOMETER

a. A flame photometer has three principal functions:

(1) to atomize the sample solution into flame, (2) to isolate the

characteristic spectral emission of an element, and (3) to detect

and measure this emission.

b. The flame photometer does not yield absolute results as do gravi-

metric analyses. All samples must be in liquid form and their

flame emission compared with that of a standard solution and the

results interpreted from a standard curve.

c. To overcome interference (enhancement or depression of the

flame of a cation due to the presence of other cations in the

solution) a flooding solution containing an excess of all the

extraneous cations is added to both the solution containing the

unknown cation and to the standard solution.

d. Pipette 2 cc of at least two standard solutions containing known

concentrations of the cation being determined into flame photo-

meter beakers and add 2 cc of the flooding solution for that cation

to each beaker.

e. Place each standard in turn under the spray nozzle and take

readings to ensure that the flame photometer is indicating the

proper per cent transmission for these particular cation con-

centrations.

f. Pipette 2 cc of solution from the unknown NH_4Ac leachate (see para.

1. g) into a flame photometer beaker and add 2 cc of the flooding

solution for the cation being determined.

g. Place the unknown solution under the spray nozzle and take the

transmission reading.

h. The concentration of the cation can now be ascertained by entering

the prepared curves of percent transmission vs cation concentra-

tion (me/litre).

j. Amount of Unknown Cation $=$ $\dfrac{\text{cation concentration x 250 x 100}}{\text{wt. of soil x 1000}}$
   (me/100 gms)

APPENDIX III

Determination of Exchangeable Hydrogen in the Soil

(Alberta Soil Survey Procedure)

Reagents: 0.5 N barium acetate adjusted to pH 7

                         0.1 NaOH - Standardized

1. Weigh 25 gms of soil (less if high in organic matter) and place in

    100 ml centrifuge tubes.

2. Add approximately one teaspoonful of ground filter paper to each tube.

3. Add 50 ml of 0.5 N barium acetate, stopper, and shake 1 hour and

    allow to stand overnight.

4. Shake again for 30 minutes. Prepare Buchner funnels and flasks.

    Use 7 cm. funnels with Whatman No. 42 filter paper and apply a

    coating of celite.

5. Transfer supernatant liquid to funnels.

6. Add an additional 50 ml of barium acetate and shake 15 minutes and

    allow to stand at least 5 minutes.

7. Shake by hand and transfer to corresponding funnels as completely as

    possible without rinsing soil that adheres to the wall of the tube.

8. Allow to drain dry, add 5 drops of phenolphthalein to filter flask and

    titrate with 0.1 N NaOH.

9. Exchangeable Hydrogen $=$ $\dfrac{\text{ml NaOH} \times \text{normality} \times 100}{\text{wt of sample}}$
    (me/100 gm soil)

APPENDIX IV

TEST DATA

Plate 12

UNIVERSITY of ALBERTA DEP'T. of CIVIL ENGINEERING SOIL MECHANICS LABORATORY **SPECIFIC GRAVITY**	PROJECT Thesis
	SITE Dunvegan
	SAMPLE Natural homogeneous mix
	LOCATION
	HOLE 140 DEPTH 75'-115'
	TECHNICIAN PAT DATE 18 May 60

Sample No.	1	2
Flask No.	495	584
Method of Air Removal	Vacuum	Vacuum
W_{b+w+s}	716.89	706.59
Temperature T	24.7	24.4
W_{b+w}	699.63	689.26
Evaporating Dish No.	3	0
Wt. Sample Dry + Dish	126.93	126.19
Tare Dish	99.77	98.68
W_s	27.16	27.50
G_s	2.74	2.71

W_{b+w+s} = Weight of flask + water + sample at T°.

W_{b+w} = Weight of flask + water at T° (flask calibration curve).

W_s = Weight of dry soil

G_s = Specific gravity of soil particles = $\dfrac{W_s}{W_s + W_{b+w} - W_{b+w+s}}$

Determination of W_s from wet soil sample:

Sample No.			Sample No.		
Container No.			Container No.		
Wt. Sample Wet + Tare			Wt. Test Sample Wet + Tare		
Wt. Sample Dry + Tare			Tare Container		
Wt. Water			Wt. Test Sample Wet		
Tare Container			W_s		
Wt. of Dry Soil					
Moisture Content w %					

Description of Sample: Homogeneous mixture of soil between depths 75' and 115'. Dark grey clay with some fine sand and silt lenses.

Remarks: Average specific gravity = 2.73

Plate 13

UNIVERSITY of ALBERTA
DEP'T of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
SPECIFIC GRAVITY

PROJECT Thesis
SITE _____
SAMPLE
LOCATION
HOLE   U of H   DEPTH 68-76'
TECHNICIAN   PAT   DATE 10 Jun 60

Sample No.	1	2	3	
Flask No.	475	507	584	
Method of Air Removal	Vac	Vac	Vac	
W_{b+w+s}	716.72	653.78	709.76	
Temperature T	24.3	28.7	24.2	
W_{b+w}	699.68	665.21	699.26	
Evaporating Dish No.	0	6	5	
Wt. Sample Dry + Dish	130.80	128.22	130.11	
Tare Dish	104.34	95.78	99.48	
W_s	26.46	27.24	30.63	
G_s	2.801	2.793	2.802	

W_{b+w+s} = Weight of flask + water + sample at T°.

W_{b+w} = Weight of flask + water at T° (flask calibration curve).

W_s = Weight of dry soil

G_s = Specific gravity of soil particles = $\dfrac{W_s}{W_s + W_{b+w} - W_{b+w+s}}$

Determination of W_s from wet soil sample:

Sample No.			Sample No.		
Container No.			Container No.		
Wt. Sample Wet + Tare			Wt. Test Sample Wet + Tare		
Wt. Sample Dry + Tare			Tare Container		
Wt. Water			Wt. Test Sample Wet		
Tare Container			W_s		
Wt. of Dry Soil					
Moisture Content w %					

Description of Sample: _Homogeneous mixture of soil between depths 68' and 76'. Dark grey clay with some silt lenses._

Remarks: _Average specific gravity = 2.801_

Plate 14

UNIVERSITY of ALBERTA
DEP'T· of CIVIL ENGINEERING
SOIL MECHANICS · LABORATORY
HYDROMETER TEST

PROJECT Thesis
SITE Dunvegan
SAMPLE 1
LOCATION
HOLE 1+0 DEPTH 75'- 115'
TECHNICIAN PAT DATE 19 May 60

Date	Temp·	Time	Elapsed Time	R'_h	R_h $=R'_h+c_m$	D m.m.	$\frac{R_h+m_t-c_d}{r_\omega}$	W % $\frac{}{r-r_\omega}$	W % Basis Orig .Sample	Remarks
24 May	18·0	1007	0							
"	"	1007¼	¼ min	30·0	30·3	·085	1·0072	·0228	97·4	
"	"	1007½	½ "	29·9	30·2	·061	"	·0227	97·0	
"	"	1008	1 "	29·8	30·1	·043	"	·0226	96·6	
"	"	1009	2 "	29·7	300	030	"	·0225	96·2	
"	"	1011	4 "	29·6	299	·021	"	·0224	95·7	
"	"	1015	8 "	29·4	29·7	·0145	1·0071	·0223	95·3	
"	"	1022	15 "	28·9	29·2	·0108	1·0069	·0220	94·0	
"	"	1037	30 "	28·4	28·7	·0075	"	·0215	91·9	
"	"	1107	60 "	27·8	28·1	·0055	"	·0209	89·3	
"	18·2	1213	126 "	27·0	27·3	·0038	1·0068	·0202	86·3	
"	"	1407	4 hrs	25·4	25·7	·0029	"	·0186	79·5	
"	18·4	1717	7½ "	24·3	24·6	·0022	1·0070	·0173	73·9	
"	18·0	2210	12 "	23·1	25·4	·0017	"	0161	68·8	
25 May	18·2	0940	23½ "	21·8	22·1	·00122	1·0069	·0149	63·7	
26 May	"	1005	48 "	20·3	20·6	·00099	"	·0134	57·3	
28 May	18·1	1020	96 "	19·8	19·1	·00066	1·0070	·0118	50·4	
1 Jun	17·9	1000	192 "	17·4	17·7	·00047	1·0069	·0105	44·9	
8 Jun	16·9	1000	360 "	16·8	17·1	·00035	1·0074	·0094	40·0	

Hydrometer No.s 36446 and _____ Graduate No. 1
W % = $\frac{100}{W_s}·\frac{S_s}{S_s-1}(R_h+m_t-c_d)$ = _____ $(R_h+m_t-c_d)$
Meniscus correction = c_m = ·0003 and _____ respectively
Dispersing agent used 6 % sodium hexameta phosphate Amount 150 ml
Correction for change in density of liquid due to addition of dispersing agent = c_d
c_d = _____ and _____ respectively
Specific Gravity of Solids = G_s 2.73

Description of Sample _____
Homogeneous mixture of soil from
depths 75', 85', 105' & 115'. Dark grey
clay with some silt lenses.

Method of Preparation _____
ASTM D 422 - 54 T

Remarks _____
Add 1.05 to H_R for readings without
immersion correction.

Initial Moisture Content	
Container No.	√35
Wt. Sample Wet + Tare	96·89
Wt. Sample Dry + Tare	83·38
Wt. Water	13·51
Tare Container	70·65
Wt. of Dry Soil	12·73
Initial Moisture ω %	106·1

Dry Weight of Sample	
Container No.	4
Wt. Sample (Wet/Dry) + Tare	245·62
Tare	169·67
Wt. (Wet/Dry) Soil	75·95

Dry Weight from Initial
Moisture = $\frac{100 \times Wt. Wet Soil}{100 + Init. Moist.\%}$ = 36·86

Plate 15

UNIVERSITY of ALBERTA
DEP'T· of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
HYDROMETER TEST

PROJECT Thesis
SITE Dunvegan
SAMPLE 2
LOCATION
HOLE 140   DEPTH 75'–115'
TECHNICIAN PAT   DATE 19 May 60

Date	Temp·	Time	Elapsed Time	R'_h	R_h $=R'_h + c_m$	D m.m.	$\frac{R_h + m_t - c_d}{r_w}$	W % $r - r_w$	W % Basis Orig .Sample	Remarks
24 May	18·0	1028	0							
"	"	1028¼	¼ min	27·8	29·1	·090	1·0069	·0209	99·2	
"		1028½	½ "	"	"	·062	"	·0209	99·2	
"		1029	1 "	27·7	28·0	·044	"	·0208	98·7	
"		1030	2 "	27·6	27·9	·032	"	·0207	98·3	
"		1032	4 "	27·4	27·7	·023	"	·0205	97·3	
"		1036	8 "	27·3	27·6	·0150	"	·0204	96·9	
"		1043	15 "	27·2	27·5	·0110	"	·0203	96·4	
"		1059	31 "	26·8	27·1	·0077	"	·0199	94·5	
"		1128	60 "	26·3	26·6	·0057	"	·0194	92·1	
"	18·2	1217	109 "	25·7	26·0	·0042	1·0068	·0189	89·7	
"	18·3	1428	4 hrs	24·1	24·4	·0031	1·0069	·0172	81·7	
"	18·4	1726	7 "	23·3	23·6	·00225	1·0070	·0163	77·4	
"	18·0	2215	11¾ "	22·2	22·5	·00175	"	·0152	72·2	
25 May	18·2	0960	23¼ "	21·2	21·5	·00125	1·0069	·0143	67·9	
26 May	18·2	1015	48 "	19·7	20·0	00089	"	·0128	60·9	
28 May	18·1	1020	96 "	18·3	18·6	·00065	1·0070	·0113	53·6	
1 Jun	17·9	1000	192 "	16·9	17·2	·00046	1·0069	·0100	47·5	
8 Jun	16·9	1000	360 "	16·1	16·4	·00036	1·0074	·0087	41·3	

Hydrometer No.s ___36446___ and _____   Graduate No. ___2___

$W \% = \frac{100}{W_s} \cdot \frac{S_s}{S_s - 1} (R_h + m_t - c_d)' =$ _____ $(R_h + m_t - c_d)$

Meniscus correction $= c_m =$ ___·0003___ and _____ respectively

Dispersing agent used ___6 % sodium hexa metaphosphate___ Amount ___150 ml___

Correction for change in density of liquid due to addition of dispersing agent $= c_d$

$c_d =$ _____ and _____ respectively

Specific Gravity of Solids $= G_s$ ___2·73___

Description of Sample _____
Homogeneous mixture of soil from depths
75', 85', 105', & 115'. Dark grey clay with
some silt lenses.

Method of Preparation _____
ASTM D422 – 54T

Remarks _____
Add 1·05 to H_R for readings without
immersion correction

Initial Moisture Content		Dry Weight of Sample	
Container No.	V35	Container No.	1
Wt. Sample Wet + Tare	96·89	Wt. Sample (Wet/Dry) + Tare	232·08
Wt. Sample Dry + Tare	83·38	Tare	163·70
Wt. Water	13·51	Wt. (Wet/Dry) Soil	68·38
Tare Container	70·65	Dry Weight from Initial	
Wt. of Dry Soil	12·73	Moisture $= \frac{100 \times Wt. Wet Soil}{100 + Init. Moist. \%} =$	33·18
Initial Moisture $w \%$	106·1		

Plate 16

UNIVERSITY of ALBERTA
DEPT. of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
GRAIN SIZE CURVE

PROJECT	Thesis		
SITE	Dunvegan		
SAMPLE			
LOCATION			
HOLE	140	DEPTH	75-115'
TECHNICIAN	Pat	DATE	19 May 60

Gravel Sizes | Sand Sizes (Coarse | Medium | Fine) | Silt Sizes (Coarse | Medium | Fine) | Clay Sizes

Seive Sizes: 3" 2" 1½" 1" ¾" ½" #4 #10 #20 #40 #60 #100 #200

Sample 1
Sample 2

Grain Size — Millimetres

Percent Finer Than

D_10 =	mm.
D_60 =	mm.
C_u	

Note: M.I.T. Grain Size Scale

Remarks:— Homogeneous mixture of soil from depths of 75', 85', 105' & 115'.

Dark gray clay with some fine sand and silt lenses. Two samples were analyzed by the hydrometer method.

Plate 17

UNIVERSITY of ALBERTA
DEP'T. of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
HYDROMETER TEST

PROJECT Thesis
SITE Dunvegan
SAMPLE 1
LOCATION
HOLE U of A — DEPTH 68'-75'
TECHNICIAN PAT — DATE 13 Jun 60

Date	Temp.	Time	Elapsed Time	R'_h	R_h $=R'_h + c_m$	D m.m.	$\frac{R_h+m_t-c_d}{r_w}$	W % $r - r_w$	W % Basis Orig. Sample	Remarks
14 Jun	20.1	1007 ¼	¼ min	26.2	26.6	.089	1.0005	1.0257	96.0	
"	"	1007 ½	½ "	26.0	26.4	.062	1 "	1.0255	95.2	
"	"	1008	1 "	25.8	26.2	.044	"	1.0253	94.5	
"	"	1009	2 "	25.1	25.5	.032	"	1.0246	91.8	
"	"	1011	4 "	24.6	25.0	.021	"	1.0241	90.0	
"	"	1015	8 "	24.0	24.4	.0155	"	1.0235	87.8	
"	"	1022	15 "	23.5	23.9	.0114	1.0004	1.0231	86.3	
"	"	1038	31 "	22.7	23.1	.0083	1.0003	1.0224	83.7	
"	"	1108	61 "	21.9	22.3	.0058	"	1.0216	80.1	
"	"	1157	110 "	21.2	21.6	.0044	"	1.0209	78.1	
"	"	1347	220 "	20.6	21.0	.0032	"	1.0203	75.8	
"	"	2010	10 hrs	19.1	19.5	.00195	"	1.0188	70.2	
15 Jun	19.7	0910	23 "	17.8	18.2	.00130	1.0002	1.0176	65.7	
16 Jun	19.5	0940	48 "	16.3	16.7	.00090	1.0003	1.0160	59.7	
18 Jun	19.6	1520	101 "	14.8	15.2	.00065	"	1.0145	54.2	
20 "	20.2	1030	144 "	13.2	13.6	.00051	1.0004	1.0128	47.8	
22 "	19.2	1300	195 "	13.1	13.5	.00045	1.0008	1.0123	45.9	
26 "	18.8	1145	290 "	11.9	12.3	.00035	"	1.0111	41.4	
4 Jul	17.8	1200	480 "	11.0	11.4	.00027	"	1.0102	38.1	
15 Jul	20.8	1200	744 "	9.7	10.1	.00020	1.0002	1.0095	35.5	

Hydrometer No.s __36446__ and _____ Graduate No. __1__

$W\% = \frac{100}{W_s} \cdot \frac{S_s}{S_s - 1}(R_h + m_t - c_d)' =$ _____ $(R_h + m_t - c_d)$

Meniscus correction = c_m = __.0004__ and _____ respectively

Dispersing agent used __6% Sodium Hexametaphosphate__ Amount __11 ml.__

Correction for change in density of liquid due to addition of dispersing agent = c_d

c_d = _____ and _____ respectively

Specific Gravity of Solids = G_s __2.80__

Description of Sample _____
Homogeneous mixture of soil between
depths 68' and 75'. Dark grey clay
with some silt lenses.

_____ , _____
_____
_____

Method of Preparation _____
ASTM D422-54T
_____
_____

Remarks _____
Add 1.05 to H_R for readings
without immersion correction.

Initial Moisture Content

Container No. __v3__
Wt. Sample Wet + Tare __102.0045__
Wt. Sample Dry + Tare __79.8649__
Wt. Water __22.1396__
Tare Container __64.0671__
Wt. of Dry Soil __15.7978__
Initial Moisture $w\%$ __140.1__

Dry Weight of Sample

Container No. __4__
Wt. Sample (Wet/Dry) + Tare __269.66__
Tare __169.65__
Wt. (Wet/Dry) Soil __100.01__
Dry Weight from Initial
Moisture = $\frac{100 \times Wt. Wet Soil}{100 + Init. Moist.\%}$ = __41.65__

Plate 18

UNIVERSITY of ALBERTA
DEP'T· of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
HYDROMETER TEST

PROJECT Thesis
SITE Dunvegan
SAMPLE 2
LOCATION
HOLE U of A   DEPTH 68'-75'
TECHNICIAN PAT   DATE 13 June 60

Date	Temp·	Time	Elapsed Time	R'_h	R_h =R'ₕ+ cm	D m.m.	$R_h+m_t=c_d$ rₒ	W % r-rₒ	W % Basis Orig Sample	Remarks
14 Jun	20·0	0945¼	¼ min	24 2	24·6	·093	1·0005	1·0237	97·1	
"	"	0945½	½ "	23 8	24 2	·065	.	1·0233	95·5	
"	"	0946	1 "	23·5	23·9	046	.	1·0230	94·2	
"	"	0947	2 "	23·1	23 5	033	.	1 0226	92·6	
"	"	0949	4 "	22·9	23·3	022	.	1·0224	91·7	
"	"	0954	9 "	22·3	22·7	·0148	"	1·0218	89·3	
"	"	1000	15 "	21·6	22·0	·0118	.	1·0211	86·4	
"	"	1015	30 "	21·0	21·4	·0085	"	1·0209	85·6	
"	"	1045	60 "	20·1	20·5	·0060	1·0003	1·0198	81·1	
"	"	1145	120 "	19·3	19·7	·0043	"	1·0194	79·5	
"	"	1345	240 "	18·7	19·1	·0031	"	1·0188	77·0	
"	"	2010	10½ hrs	17 5	17·9	·00195	"	1·0172	70·5	
15 Jun	19·5	0910	23½ "	16·5	16·9	·00132	1·0002	1·0163	66·8	
16 Jun	19 3	0940	48 "	15·2	15·6	00095	1·0003	1·0149	61·0	
18 Jun	19·4	1520	101 "	13·8	14·2	·00066	"	1·0135	55·3	
20 Jun	20·0	1030	144 "	12·4	12·8	·00051	1·0004	1·0120	49·2	
22 Jun	19·0	1300	195 "	12·0	12·4	·00043	1·0008	1·0112	45·8	
26 Jun	18·6	1145	290 "	11 2	11·6	·00034	.	1·0104	42·6	
4 Jul	17·8	1200	480 "	10·2	10·6	·00026	" "	1·0094	38·5	
16 Jul	20·8	1200	744 "	9·9	9·3	·00019	1·0002	1·0087	35·6	

Hydrometer No.s ___36446___ and _____   Graduate No. ___2___

$W \% = \frac{100}{W_s} \cdot \frac{S_s}{S_s-1}(R_h + m_t - c_d) = $ _____ $(R_h + m_t - c_d)$

Meniscus correction = c_m = ___·0004___ and _____ respectively

Dispersing agent used ___6 % sodium hexametaphosphate___ Amount ___11 ml___

Correction for change in density of liquid due to addition of dispersing agent = c_d

c_d = _____ and _____ respectively

Specific Gravity of Solids = G_s ___2·80___

Description of Sample _____
Homogeneous mixture of soil between
depths 68' and 75! Dark grey clay with
some silt lenses.
_____
_____
_____

Method of Preparation _____
ASTM D422 - 54T
_____
_____

Remarks _____
Add 1.05 to HR for readings
without immersion correction.

Initial Moisture Content

Container No. ___V2___
Wt. Sample Wet + Tare ___105·3097___
Wt. Sample Dry + Tare ___81·8748___
Wt. Water ___23·4349___
Tare Container ___65·1721___
Wt. of Dry Soil ___16·7027___
Initial Moisture w % ___140·3___

Dry Weight of Sample

Container No. ___2___
Wt. Sample (Wet/Dry) + Tare ___259·03___
Tare ___167·79___
Wt. (Wet/Dry) Soil ___91·24___
Dry Weight from Initial
Moisture = $\frac{100 \times Wt. Wet Soil}{100 + Init. Moist. \%}$ = ___37·97___

Plate 19

UNIVERSITY of ALBERTA
DEP T· of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
GRAIN SIZE CURVE

PROJECT Thesis
SITE Dunvegan
SAMPLE
LOCATION
HOLE U of A   DEPTH 68'-75'
TECHNICIAN PAT   DATE 13 June 60

	D₁₀ =	mm.
	D₆₀ =	mm.
	Cu	

$D_{10} =$ ___ mm.
$D_{60} =$ ___ mm.
C_u ___

Note: M·I·T· Grain Size Scale

Grain Size — Millimetres

Percent Finer Than

Gravel Sizes   Sand Sizes   Silt Sizes   Clay Sizes
Coarse | Medium | Fine
Coarse | Medium | Fine

Seive Sizes

Sample 2
Sample 1

Remarks: Homogeneous mixture of soil from depths of 68'-75'. Dark grey clay with some fine sand and silt lenses. Two samples were analyzed by the hydrometer method.

Cu/Ni 1°/min

Test Hole 140 Untreated
X-RAY DIFFRACTION

70 60 50 40 30 20 10

70 60 50 40 30 20 10

70 60 50 40 30 20 10

70 60 50 40 30 20 10

6° 8° 10° 12° 14° 16° 18° 20° 22° 24° 26°

Plate 2

Cu/Ni 1°/min
Test Hole 140 Glycolated
X-RAY DIFFRACTION

Plate 21

Test Cu/Ni 1%/min.
Test Hole 1 to Heated to 500°C.
X-RAY DIFFRACTION

Plate 22

Cu/Ni 1°/min

Test Hole U of A Untreated

X-RAY DIFFRACTION

Plate 23

X-RAY DIFFRACTION
Test Hole U of A Glycolated
Co/Ni 1°/min

Plate 25

X-RAY DIFFRACTION

Test Hole U of A - Heated to 500°C.

Cu/Ni   1°/min

Plate 25

Plate 26

UNIVERSITY of ALBERTA
DEPT· of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
CONSOLIDATION RESULTS

PROJECT	Thesis	
SITE	Dunvegan	
SAMPLE	Natural Clay (Remoulded - Rebound with NaOH)	
LOCATION		
HOLE	140	DEPTH 75'-115'
TECHNICIAN	PAT	DATE 22 Jul 60

Specific Gravity of Soil Solids $G_S = 2.73$ Height of Soil Solids $H_S = .2757$ ins.

Void Ratio e (End) = 1.522

Void Ratio e(Start) = 2.603

Void Ratio e (Start Dimensions) = 2.627

$e(End) = W\%(End) \times G_S$ $H_S = \left(\frac{Wt \cdot Soil}{G_S \times Area \times 2.54}\right)ins.$ $e = previous\ e \pm \frac{Defl.}{H_S}$

Time Interval	Load on Pan (gms)	Corr· Dial Reading(ins)	Deflection (ins.)	Deflection H_S	Void Ratio e	Pressure Kg/cm²=T/ft²
	0	.8862			2.603	
4 days	20	.8141	-.0721	-.262	2.341	0.070
1 day	50	.7240	-.0901	-.327	2.014	0.156
"	100	.6563	-.0677	-.246	1.768	0.318
"	200	.6023	-.0540	-.196	1.572	0.596
"	400	.5513	-.0510	-.185	1.387	1.18
"	800	.5032	-.0481	-.174	1.213	2.35
"	1600	.4620	-.0412	-.149	1.064	4.69
"	400	.4799	+.0179	+.065	1.129	1.18
"	100	.5038	+.0239	+.087	1.216	0.318
"	200	.4987	-.0051	-.018	1.198	0.596
"	400	.4878	-.0109	-.040	1.158	1.18
"	800	.4746	-.0132	-.048	1.110	2.35
"	1600	.4568	-.0178	-.065	1.045	4.69

Compressive Index = _____

Swelling Pressure = _____ T/ft²

Pre-Cons. Load = _____ T/ft²

Void Ratio e

0.01 0.1 1.0 10 100

Pressure Kg./cm² (Tons/ft²)

Plate 27

UNIVERSITY of ALBERTA
DEPT· of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
CONSOLIDATION RESULTS

PROJECT	Thesis	
SITE	Dunvegan	
SAMPLE	Natural Clay (Remoulded - Rebound with NaOH)	
LOCATION		
HOLE	140	DEPTH 75'-115'
TECHNICIAN	PAT	DATE 22 Jul 60

Specific Gravity of Soil Solids G_S = _____ Height of Soil Solids H_S = _____ ins.

Void Ratio e (End) = _____

Void Ratio e(Start) = _____

Void Ratio e (Start Dimensions) = _____

$e(End) = W\%(End) \times G_S$ $\qquad H_S = \left(\dfrac{Wt \cdot Soil}{G_S \times Area \times 2.54}\right) ins.$ $\qquad e = previous\ e \pm \dfrac{Def'l.}{H_S}$
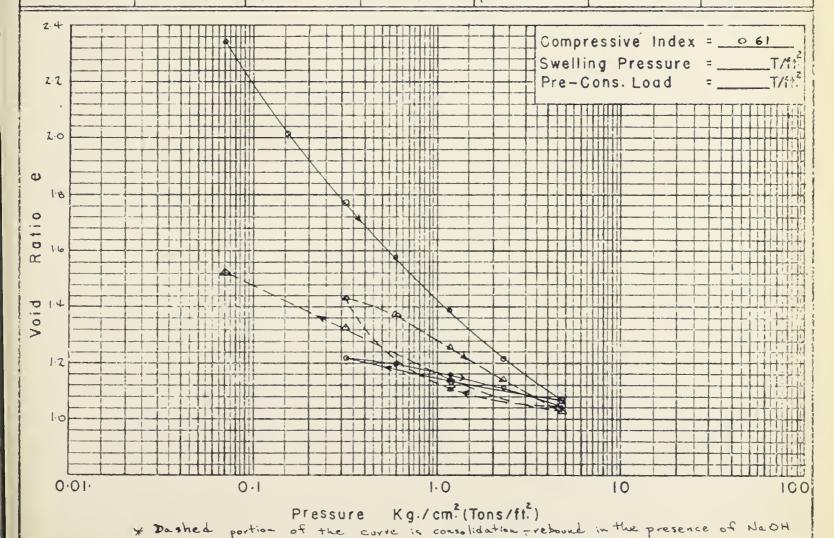
Time Interval	Load on Pan (gms)	Corr. Dial Reading(ins.)	Deflection (ins.)	Deflection H_S	Void Ratio e	Pressure $Kg/cm^2 = T/ft^2$
Continued from previous page						
1 day	* 400	4740	+.0172	+.062	1.107	1.18
38 days	100	.5638	+.0898	+.326	1.433	0.319
3 days	200	.5461	-.0177	-.064	1.369	0.596
2 days	400	.5158	-.0303	-.110	1.259	1.18
"	800	.4828	-.0330	-.120	1.139	2.35
1 day	1600	4533.	-.0295	-.107	1.032	4.69
2 days	400	.4819	+.0286	+.104	1.136	1.18
5 days	100	.5368	+.0549	+.199	1.325	0.318
6 days	20	.5883	+.0515	+.187	1.522	0.070
		* Allowed to rebound with NaOH in the place of water.				
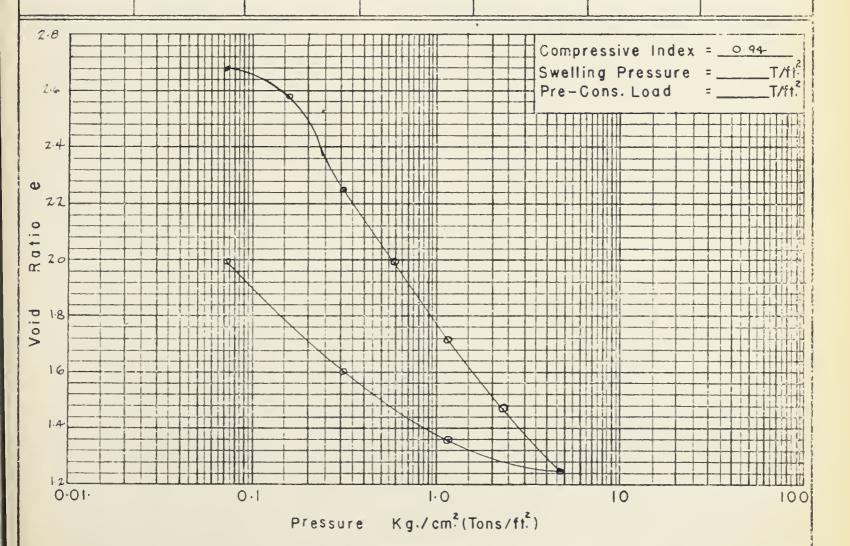
Compressive Index = 0.61
Swelling Pressure = _____ T/ft²
Pre-Cons. Load = _____ T/ft²

Pressure Kg./cm². (Tons/ft².)

* Dashed portion of the curve is consolidation-rebound in the presence of NaOH

Plate 28

UNIVERSITY of ALBERTA
DEPT· of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
CONSOLIDATION RESULTS

PROJECT	Thesis
SITE	Dunvegan
SAMPLE	Sodium Clay (Remoulded)
LOCATION	
HOLE 140	DEPTH 75'-115'
TECHNICIAN PAT	DATE 25 Jun 60

Specific Gravity of Soil Solids G_s = 2.73   Height of Soil Solids H_s = .2705 ins.

Void Ratio e (End) = 1.993

Void Ratio e(Start) = 2.705

Void Ratio e (Start Dimensions) = 2.697

$e(End) = W\%(End) \times G_s$ $H_s = \left(\dfrac{Wt \cdot Soil}{G_s \times Area \times 2.54}\right)$ ins. $e = previous\ e \pm \dfrac{Def'l.}{H_s}$

Time Interval	Load on Pan (gms)	Corr· Dial Reading(ins.)	Deflection (ins.)	Deflection H_s	Void Ratio e	Pressure Kg/cm²=T/ft²
	0	.4500			2.705	
1 day	20	.4428	-.0072	-.027	2.678	.0724
2 days	50	.4158	-.0270	-.100	2.578	.160
3 days	100	.3262	-.0896	-.331	2.247	.306
"	200	.2566	-.0696	-.257	1.990	.598
2 days	400	.1826	-.0740	-.274	1.716	1.18
"	800	.1157	-.0669	-.247	1.469	2.35
6 days	1600	.0552	-.0605	-.224	1.245	4.69
2 days	400	.0860	+.0308	+.114	1.359	1.18
5 days	100	.1512	+.0652	+.241	1.600	.306
21 days	20	.2578	+.1066	+.393	1.993	.0724
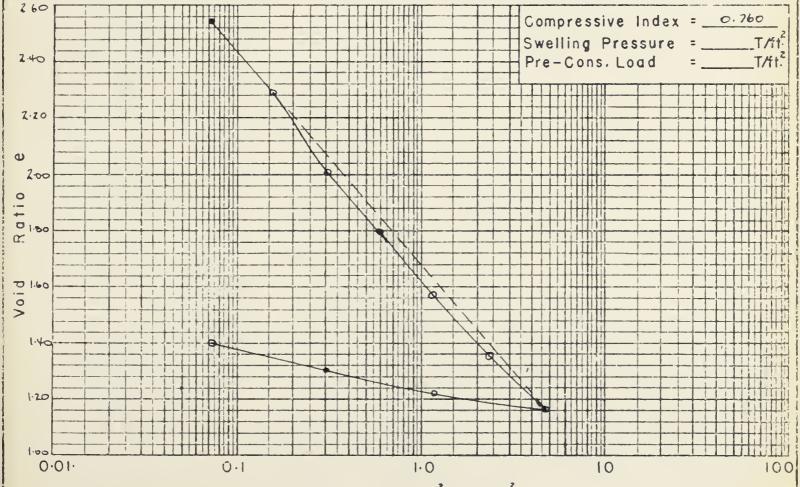
Compressive Index = 0.94
Swelling Pressure = ____ T/ft²
Pre-Cons. Load = ____ T/ft²

Void Ratio e vs Pressure Kg./cm² (Tons/ft²)

Plate 24

UNIVERSITY of ALBERTA
DEPT. of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
CONSOLIDATION RESULTS

PROJECT	Thesis
SITE	Dunvegan
SAMPLE	Calcium Clay (Remoulded)
LOCATION	
HOLE 140	DEPTH 75′–115′
TECHNICIAN PAT	DATE 22 Jul 60

Specific Gravity of Soil Solids G_S = 2.73 Height of Soil Solids H_S = .2686 ins.

Void Ratio e (End) = 1.399

Void Ratio e(Start) = 2.784

Void Ratio e (Start Dimensions) = 2.723

$e(End) = W\%(End) \times G_S$ $H_S = \left(\dfrac{Wt \cdot Soil}{G_S \times Area \times 2.54}\right) ins.$ $e = previous\ e \pm \dfrac{Def'l.}{H_S}$

Time Interval	Load on Pan (gms)	Corr. Dial Reading(ins.)	Deflection (ins.)	Deflection H_S	Void Ratio e	Pressure $Kg/cm^2 = T/ft^2$
	0	.4600			2.784	
1 day	20	.3959	−.0641	−.239	2.545	.0721
..	50	.3270	−.0689	−.256	2.289	.160
..	100	.2609	−.0661	−.246	2.043	.306
..	200	.1951	−.0658	−.245	1.798	.598
..	400	.1333	−.0618	−.230	1.568	1.18
..	800	.0752	−.0581	−.216	1.352	2.35
..	1600	.0238	−.0514	−.191	1.161	4.69
"	400	.0389	+.0151	+.056	1.217	1.18
"	100	.0622	+.0233	+.087	1.304	.306
3 days	20	.0878	+.0256	+.095	1.399	.0721
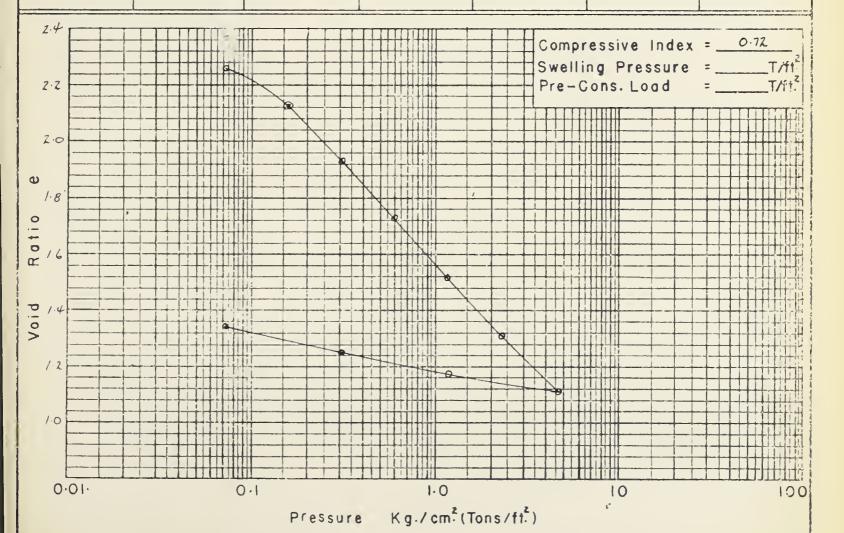
Compressive Index = 0.760
Swelling Pressure = _____ T/ft²
Pre-Cons. Load = _____ T/ft²

Pressure Kg./cm² (Tons/ft.)

Plate 30

UNIVERSITY of ALBERTA
DEPT. of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
CONSOLIDATION RESULTS

PROJECT	Thesis
SITE	Duvegan
SAMPLE	Mg Clay (Remoulded)
LOCATION	
HOLE	140	DEPTH 75'- 115'
TECHNICIAN	PAT	DATE 15 Aug 60

Specific Gravity of Soil Solids G_s = ___2.73___ Height of Soil Solids H_s = ___.2992___ ins.

Void Ratio e (End) = _____ 1.343

Void Ratio e(Start) = _____ 2.362

Void Ratio e (Start Dimensions) = _____ 2.342

$e(End) = W\%(End) \times G_s$ $\qquad H_s = \left(\dfrac{Wt \cdot Soil}{G_s \times Area \times 2.54}\right)ins.$ $\qquad e = previous\ e \pm \dfrac{Def'l.}{H_s}$

Time Interval	Load on Pan (gms)	Corr. Dial Reading(ins.)	Deflection (ins.)	Deflection / H_s	Void Ratio e	Pressure $Kg/cm^2 = T/ft^2$
	0	1.0000			2.362	
2 days	20	.9692	-.0308	-.103	2.259	.0724
1 day	50	.9282	-.0410	-.137	2.122	.160
"	100	.8717	-.0565	-.189	1.933	.306
"	200	.8094	-.0623	-.208	1.725	.598
"	400	.7468	-.0626	-.209	1.576	1.18
"	800	.6848	-.0620	-.207	1.309	2.35
"	1600	.6260	-.0588	-.197	1.112	4.69
"	400	.6432	+.0172	+.057	1.169	1.18
"	100	.6682	+.0250	+.084	1.253	.306
2 days	20	.6951	+.0269	+.090	1.343	.0724

Compressive Index = ___0.72___

Swelling Pressure = _____ T/ft²

Pre-Cons. Load = _____ T/ft²

Pressure Kg./cm².(Tons/ft.²)

Plate 31

UNIVERSITY of ALBERTA
DEPT· of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
CONSOLIDATIONRESULTS

PROJECT	Thesis
SITE	Dunvegan
SAMPLE	Potassium Clay (Remoulded)
LOCATION	
HOLE 1+0	DEPTH 75′-115′
TECHNICIAN PAT	DATE 24 June60

Specific Gravity of Soil Solids G_S = __2·73__ Height of Soil Solids H_S = ·2535 ins.

Void Ratio e (End) = 1·494

Void Ratio e(Start) = 2·976

Void Ratio e (Start Dimensions) = 2·945

$e(End) = W\%(End) \times G_S$ $H_S = \left(\frac{Wt \cdot Soil}{G_S \times Area \times 2·54}\right) ins.$ $e = previous\ e \pm \frac{Def'l.}{H_S}$

Time Interval	Load on Pan (gms)	Corr. Dial Reading(ins.)	Deflection (ins.)	$\frac{Deflection}{H_S}$	Void Ratio e	Pressure $Kg/cm^2 = T/ft^2$
	0	·5000			2·976	
1 day	20	·4173	·0827	·326	2·650	·0721
"	50	·3528	·0645	·254	2·396	·160
"	100	·2981	0547	215	2·181	·306
"	200	2379	·0602	·237	1·944	·598
"	400	1768	0611	241	1·703	1·18
"	800	·1149	·0619	·244	1·459	2·35
2 days	1600	·0547	0602	·237	1·222	4·69
1 day	400	·0695	-·0148	·058	1·280	1·18
"	100	0947	·0252	099	1·379	·306
2 days	20	·1239	0292	115	1·494	·0721

Compressive Index = 0·780
Swelling Pressure = ____ T/ft²
Pre-Cons. Load = ____ T/ft²

Pressure   Kg./cm² (Tons/ft.)

Plate 32

UNIVERSITY of ALBERTA
DEPT· of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
CONSOLIDATIONRESULTS

PROJECT	Thesis	
SITE	Dunvegan	
SAMPLE	Hydrogen clay	(Remoulded)
LOCATION		
HOLE	140	DEPTH 75'-115'
TECHNICIAN	PAT	DATE 5 Jul 60
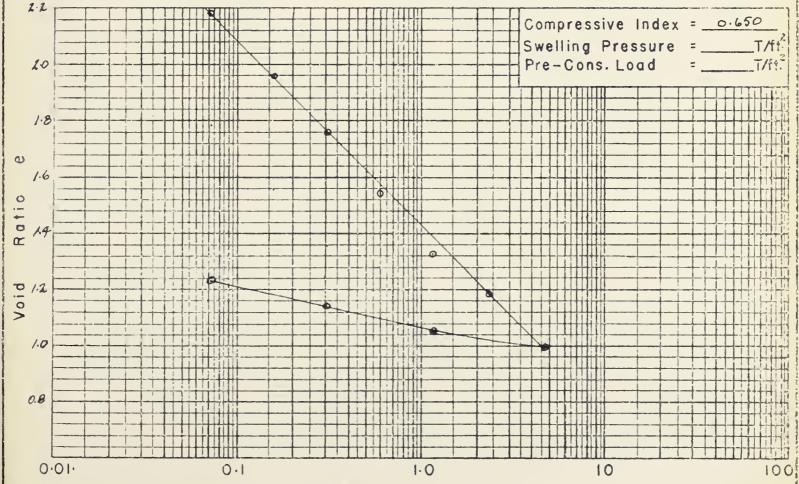
Specific Gravity of Soil Solids $G_S =$ ___2·73___ Height of Soil Solids $H_S =$ ___·2975___ ins.

Void Ratio e (End) = _____ 1·236

Void Ratio e(Start) = _____ 2·412

Void Ratio e (Start Dimensions) = _____ 2·361

$e(End) = W\%(End) \times G_S$ $\qquad H_S = \left(\dfrac{Wt \cdot Soil}{G_S \times Area \times 2·54}\right) ins.$ $\qquad e = previous\ e \pm \dfrac{Def'l.}{H_S}$

Time Interval	Load on Pan (gms)	Corr. Dial Reading(ins.)	Deflection (ins.)	$\dfrac{Deflection}{H_S}$	Void Ratio e	Pressure $Kg/cm^2 = T/ft^2$
	0	·5100			2·412	
1 day	20	·4400	− ·0700	− ·235	2·177	·0721
··	50	·3743	− ·0657	− ·221	1·956	·160
··	100	·3153	− ·0590	− ·198	1·758	·306
··	200	·2499	− ·0654	− ·220	1·538	·598
5 days	400	·1866	− ·0633	− ·213	1·325	1·18
1 day	800	·1438	− ·0428	− ·144	1·181	2·35
·	1600	·0886	− ·0552	− ·186	0·995	4·69
··	400	·1067	+ ·0181	+ ·061	1·056	1·18
··	100	·1328	+ ·0261	+ ·088	1·144	·306
2 days	20	·1602	+ ·0274	+ ·092	1·236	·0721
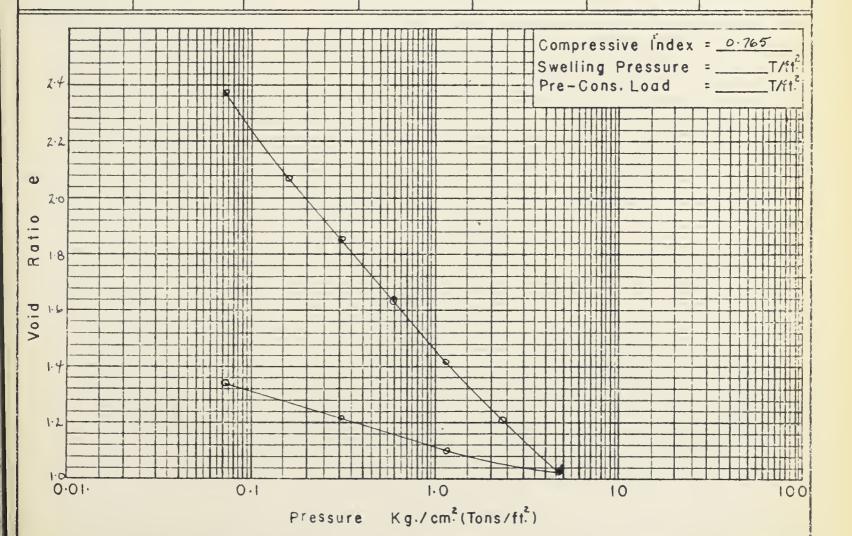
Compressive Index = ___0·650___

Swelling Pressure = _____ T/ft²

Pre-Cons. Load = _____ T/ft²

Pressure Kg./cm² (Tons/ft.²)

PLATE 33

UNIVERSITY of ALBERTA
DEPT· of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
CONSOLIDATIONRESULTS

PROJECT	Thesis
SITE	Dunvegan
SAMPLE	Natural Clay (Remoulded)
LOCATION	
HOLE U of A	DEPTH 68'-75'
TECHNICIAN PAT	DATE 3 Aug 60

Specific Gravity of Soil Solids G_S = 2.80 _____ Height of Soil Solids H_S = .2791 ins.

Void Ratio e (End) = _____ 1.339

Void Ratio e(Start) = _____ 2.649

Void Ratio e (Start Dimensions) = _____ 2.583

$e(End) = W\%(End) \times G_S$ $H_S = \left(\dfrac{Wt \cdot Soil}{G_S \times Area \times 2.54}\right)$ ins. $e = previous\ e \pm \dfrac{Def'l.}{H_S}$

Time Interval	Load on Pan (gms)	Corr· Dial Reading(ins.)	Deflection (ins.)	$\dfrac{Deflection}{H_S}$	Void Ratio e	Pressure $Kg/cm^2 = T/ft^2$
	P	.4700			2.649	
1 day	20	.3923	-.0777	-.278	2.371	.0721
"	50	.3084	-.0839	-.301	2.070	.160
"	100	.2473	-.0611	-.219	1.851	.306
"	200	.1871	-.0602	-.216	1.635	.578
"	400	.1251	-.0613	-.220	1.415	1.18
"	800	.0671	-.0587	-.210	1.205	2.35
"	1600	.0162	-.0509	-.182	1.023	4.69
"	400	.0380	+.0218	-.078	1.101	1.18
"	100	.0698	+.0318	-.114	1.215	.306
"	20	.1045	+.0347	-.124	1.339	.0721

Compressive Index = 0.765

Swelling Pressure = _____ T/ft^2

Pre-Cons. Load = _____ T/ft^2

Void Ratio e

Pressure $Kg./cm^2 (Tons/ft^2)$

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SOIL MECHANICS LABORATORY
CONSOLIDATION RESULTS

PROJECT	Thesis
SITE	Dunvegan
SAMPLE	Sodium Clay (Remoulded)
LOCATION	
HOLE U of A	DEPTH 68'-75'
TECHNICIAN PAT	DATE 12 Aug 60

Specific Gravity of Soil Solids G_s = ___2·80___ Height of Soil Solids H_s = ___·2122___ ins.

Void Ratio e (End) = _____ 1·751

Void Ratio e(Start) = _____ 2·544

Void Ratio e (Start Dimensions) = _____ 2·487

$e(End) = W\%(End) \times G_s$ $H_s = \left(\dfrac{Wt \cdot Soil}{G_s \times Area \times 2.54}\right) ins.$ $e = previous\ e \pm \dfrac{Def'l.}{H_s}$

Time Interval	Load on Pan (gms)	Corr. Dial Reading (ins.)	Deflection (ins.)	$\dfrac{Deflection}{H_s}$	Void Ratio e	Pressure Kg/cm²=T/ft²
	0	1·0000			2·544	
1 day	10	·9802	−·0198	−·093	2·451	·056
5 days	30	·9391	−·0411	−·194	2·257	·143
3 days	70	·8951	−·0440	−·207	2·050	·319
"	130	·8554	−·0397	−·187	1·863	·582
"	260	·8073	−·0481	−·227	1·636	1·15
2 days	540	·7565	−·0508	−·240	1·396	2·38
"	1070	·7109	−·0456	−·215	1·181	4·70
4 days	10	·8318	+·1209	+·570	1·751	·056
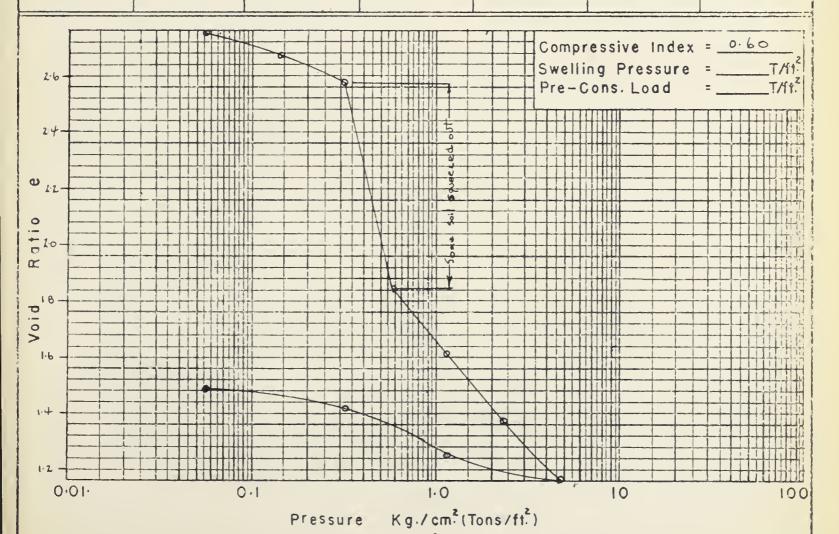
Compressive Index = ___0·78___

Swelling Pressure = _____ T/ft²

Pre-Cons. Load = _____ T/ft²

Void Ratio e

Pressure Kg./cm² (Tons/ft.)

Plate 35

UNIVERSITY of ALBERTA
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SOIL MECHANICS LABORATORY
CONSOLIDATION RESULTS

PROJECT	Thesis
SITE	Dunvegan
SAMPLE	Hydrogen Clay (Remoulded)
LOCATION	
HOLE	U of A DEPTH 68'-75'
TECHNICIAN	PAT DATE 28 Jul 60

Specific Gravity of Soil Solids G_S = __2.80__ Height of Soil Solids H_S = __.1959__ ins.

Void Ratio e (End) = _____ 1.481

Void Ratio e (Start) = _____ 2.838

Void Ratio e (Start Dimensions) = _____ 2.777

$e(End) = W\%(End) \times G_S$ $H_S = \left(\dfrac{Wt \cdot Soil}{G_S \times Area \times 2.54}\right) ins.$ $e = previous\ e \pm \dfrac{Def'l.}{H_S}$

Time Interval	Load on Pan (gms)	Corr· Dial Reading (ins.)	Deflection (ins.)	$\dfrac{Deflection}{H_S}$	Void Ratio e	Pressure $Kg/cm^2 = T/ft^2$
	0	1.0500			2.838	
1 day	10	1.0328	-.0172	-.088	2.750	.056
"	30	1.0175	-.0153	-.078	2.672	.143
"	70	0.9979	-.0196	-.100	2.572	.319
"	130	0.8547	-.1432	-.730	1.842	.582
"	260	0.8098	-.0449	-.229	1.613	1.15
"	540	0.7619	-.0479	-.245	1.368	2.38
"	1070	0.7217	-.0402	-.205	1.163	4.70
"	260	0.7388	+.0171	+.087	1.250	1.15
"	70	0.7718	+.0330	+.168	1.418	.319
4 days	10	0.7841	+.0123	+.063	1.481	.056
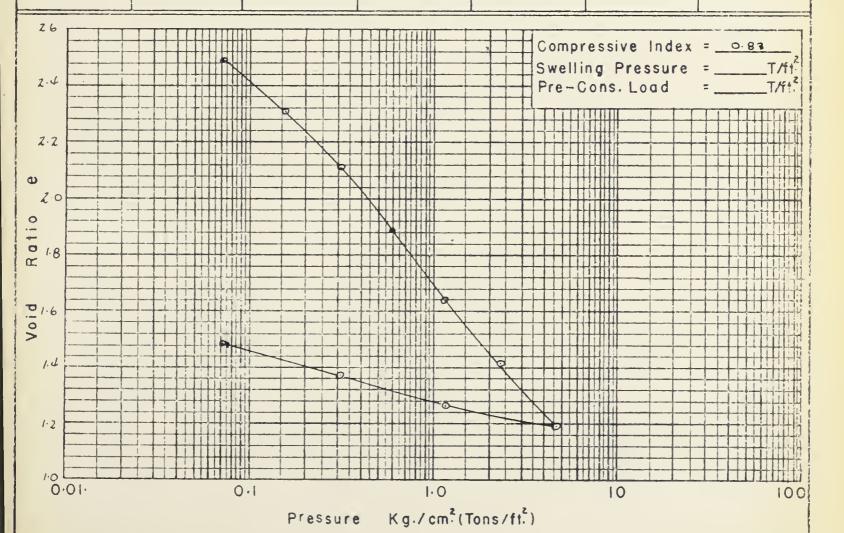
Compressive Index = __0.60__

Swelling Pressure = _____ T/ft^2

Pre-Cons. Load = _____ T/ft^2

Void Ratio e (vertical axis)

Pressure $Kg./cm^2 (Tons/ft^2)$ (horizontal axis)

Some soil squeezed out

Plate 86

UNIVERSITY of ALBERTA
DEPT· of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
CONSOLIDATION RESULTS

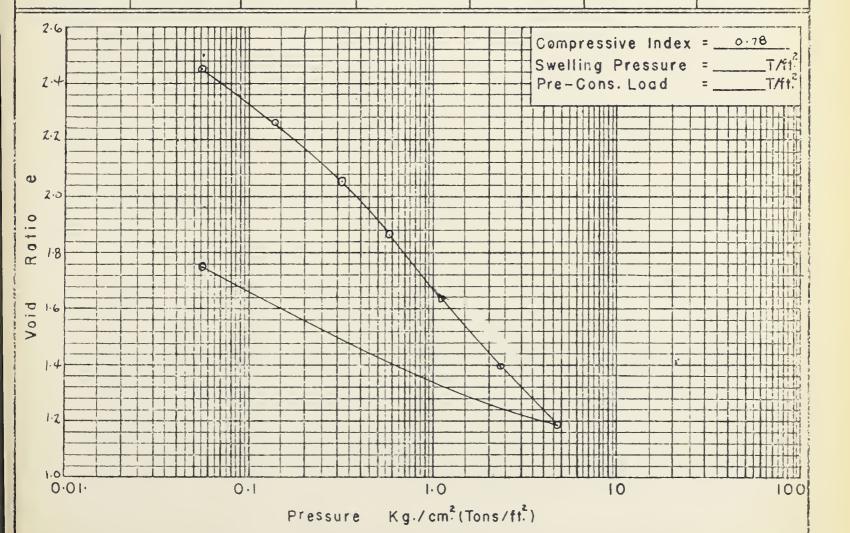|	
PROJECT	Thesis
SITE	Dunvegan
SAMPLE	Calcium Clay (Remoulded)
LOCATION	
HOLE	UofA DEPTH 68'-75'
TECHNICIAN	PAT DATE 21 Aug 60

Specific Gravity of Soil Solids G_S = 2·80 Height of Soil Solids H_S = ·2769 ins.

Void Ratio e (End) = 1·481

Void Ratio e(Start) = 2·618

Void Ratio e (Start Dimensions) = 2·612

$$e(End) = W\%(End) \times G_S \qquad H_S = \left(\frac{Wt \cdot Soil}{G_S \times Area \times 2\cdot54}\right) ins. \qquad e = previous\ e \pm \frac{Def'l.}{H_S}$$

Time Interval	Load on Pan (gms)	Corr. Dial Reading(ins.)	Deflection (ins.)	$\frac{Deflection}{H_S}$	Void Ratio e	Pressure $Kg/cm^2 = T/ft^2$
	0	·5000			2·618	
1 day	20	·4647	- ·0353	- ·127	2·491	·0721
"	50	·4130	- ·0517	- ·187	2·304	·160
"	100	·3591	- ·0539	- ·195	2·109	·306
"	200	·2962	- ·0629	- ·227	1·882	·598
"	400	·2290	- ·0672	- ·243	1·639	1·18
"	800	·1659	- ·0631	- ·228	1·416	2·35
"	1600	·1057	- ·0602	- ·217	1·194	4·69
"	400	·1242	+ ·0185	+ ·067	1·261	1·18
"	100	·1543	+ ·0301	+ ·109	1·370	·306
3 days	20	·1851	+ ·0308	+ ·111	1·481	·0721

Compressive Index = 0·83

Swelling Pressure = _____ T/ft²

Pre-Cons. Load = _____ T/ft²

Void Ratio e

Pressure Kg./cm²(Tons/ft.²)

Plate 37

UNIVERSITY of ALBERTA
DEPT· of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
CONSOLIDATIONRESULTS
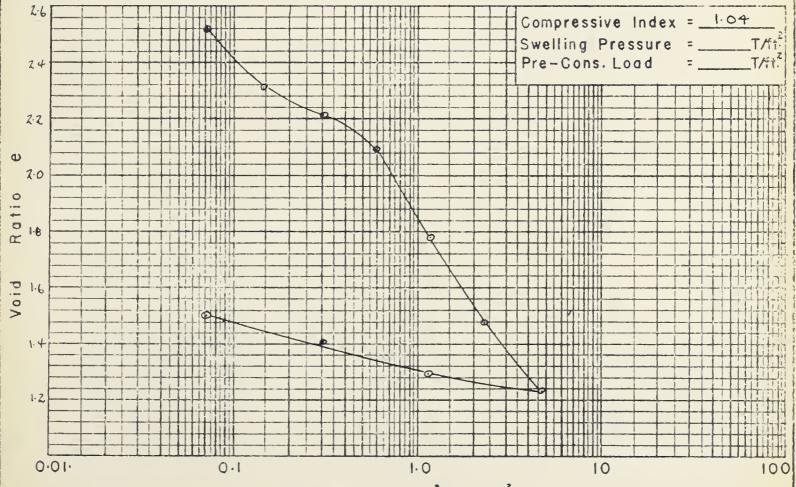
PROJECT	Thesis
SITE	Dunvegan
SAMPLE	Magnesium clay (Remoulded)
LOCATION	
HOLE U of A	DEPTH 68'–75'
TECHNICIAN PAT	DATE 23 Aug 60

Specific Gravity of Soil Solids G_S = __2·80__ Height of Soil Solids H_S = __·2631__ ins.

Void Ratio e (End) = _____ 1·504

Void Ratio e (Start) = _____ 2·798

Void Ratio e (Start Dimensions) = _____ 2·817

$e(End) = W\%(End) \times G_S$ $H_S = \left(\dfrac{Wt \cdot Soil}{G_S \times Area \times 2.54}\right)ins.$ $e = previous\ e \pm \dfrac{Def'l.}{H_S}$

Time Interval	Load on Pan (gms)	Corr. Dial Reading(ins.)	Deflection (ins.)	$\dfrac{Deflection}{H_S}$	Void Ratio e	Pressure Kg/cm²= T/ft²
	0	·9000			2·798	
2 days	20	·8260	−·0740	−·282	2·516	·0704
1 day	50	·7723	−·0537	−·205	2·311	·147
··	100	·7464	−·0259	−·099	2·212	·304
··	200	·7148	−·0316	−·121	2·091	·597
··	400	·6323	−·0825	−·315	1·776	1·18
··	800	·5541	−·0782	−·298	1·478	2·36
··	1600	·4895	−·0646	−·247	1·231	4·69
½ day	400	·5048	+·0153	+·058	1·289	1·13
"	100	·5343	+·0295	+·113	1·402	·304
2 days	20	·5609	+·0266	+·102	1·504	·0704
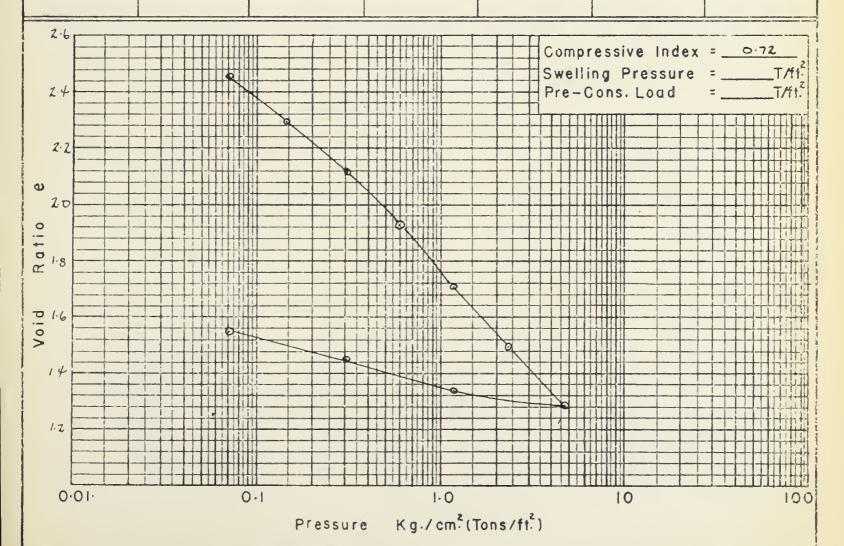
Compressive Index = __1·04__

Swelling Pressure = _____ T/ft²

Pre–Cons. Load = _____ T/ft²

Void Ratio e (y-axis), Pressure Kg./cm² (Tons/ft.) (x-axis)

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SOIL MECHANICS LABORATORY
CONSOLIDATION RESULTS

PROJECT	Thesis
SITE	Dunvegan
SAMPLE	Potassium Clay (Remoulded)
LOCATION	
HOLE U of A	DEPTH 68'-75'
TECHNICIAN PAT	DATE 24 Aug 60

Specific Gravity of Soil Solids G_S = 2.80   Height of Soil Solids H_S = .2734 ins.

Void Ratio e (End) = 1.547

Void Ratio e (Start) = 2.608

Void Ratio e (Start Dimensions) = 2.657

$e(End) = W\%(End) \times G_S$ $H_S = \left(\dfrac{Wt \cdot Soil}{G_S \times Area \times 2.54}\right) ins.$ $e = previous\ e \pm \dfrac{Def'l.}{H_S}$

Time Interval	Load on Pan (gms)	Corr. Dial Reading(ins.)	Deflection (ins.)	Deflection H_S	Void Ratio e	Pressure $Kg/cm^2 = T/ft^2$
	0	.7500			2.608	
1 day	20	.7082	-.0418	-.153	2.455	.0704
"	50	.6638	-.0444	-.162	2.293	.147
"	100	.6157	-.0481	-.176	2.117	.304
"	200	.5632	-.0525	-.192	1.925	.597
"	400	.5043	-.0589	-.215	1.710	1.18
"	800	.4451	-.0592	-.217	1.493	2.35
"	1600	.3873	-.0578	-.211	1.282	4.69
"	400	.4022	+.0149	+.054	1.336	1.18
"	100	.4329	+.0307	+.112	1.448	.304
"	20	.4600	+.0271	+.099	1.547	.0704

Compressive Index = 0.72

Swelling Pressure = _____ T/ft²

Pre-Cons. Load = _____ T/ft²

Pressure   Kg./cm²(Tons/ft.²)

Plate 39

UNIVERSITY of ALBERTA
DEPT· of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
CONSOLIDATIONRESULTS

PROJECT   Thesis
SITE   Dunvegan
SAMPLE   Undisturbed (Rebound with M₂O)
LOCATION
HOLE·   U of A   DEPTH 71'
TECHNICIAN   PAT   DATE 15 Jun 60

Specific Gravity of Soil Solids G_S = 2.80 ___ Height of Soil Solids H_S = 0.4280 ins.

Void Ratio e (End) = _____ 1.410

Void Ratio e(Start) = _____ 1.080

Void Ratio e (Start Dimensions) = _____ 1.053

$e(End) = W\%(End) \times G_S$ $H_S = \left(\dfrac{Wt \cdot Soil}{G_S \times Area \times 2.54}\right) ins.$ $e = previous\ e \pm \dfrac{Def'l.}{H_S}$

Time Interval	Load on Pan (gms)	Corr. Dial Reading(ins.)	Deflection (ins.)	$\dfrac{Deflection}{H_S}$	Void Ratio e	Pressure Kg/cm²= T/ft²
	0	·5000			1·080	
10 days	20	·6748	+·1748	+·408	1·488	·0708
1 day	50	·6689	−·0059	−·014	1·474	·159
2 days	100	6482	−·0207	−·048	1·426	325
"	200	·6170	−·0312	−·073	1·353	·598
"	400	·5792	−·0378	−·088	1·265	1·18
"	100	·6147	+·0355	+·083	1·348	·325
10 days	20	·6635	+·0488	+·112	1·460	·0708
2 days	50	·6552	−·0083	−·019	1·441	·159
4 days	100	·6369	−·0183	−·043	1·398	·325
3 days	200	·6103	−·0266	−·062	1·336	·598
2 days	400	·5788	−·0315	−·073	1·263	1·18
3 days	* 100	·6107	+·0319	+·075	1·338	·325
5 days	20	·6602	+·0495	+·116	1·454	·0708

Compressive Index = _____

Swelling Pressure = _____ T/ft²

Pre-Cons. Load = _____ T/ft²

Void Ratio e

0.01   0.1   1.0   10   100

Pressure   Kg./cm².(Tons/ft².)

* Allowed to rebound with M₂O-H₂O in the place of water.

v

Plate 40

UNIVERSITY of ALBERTA
DEPT· of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
CONSOLIDATION RESULTS

PROJECT Thesis
SITE Dunvegan
SAMPLE Undisturbed (Rebound with MgO)
LOCATION
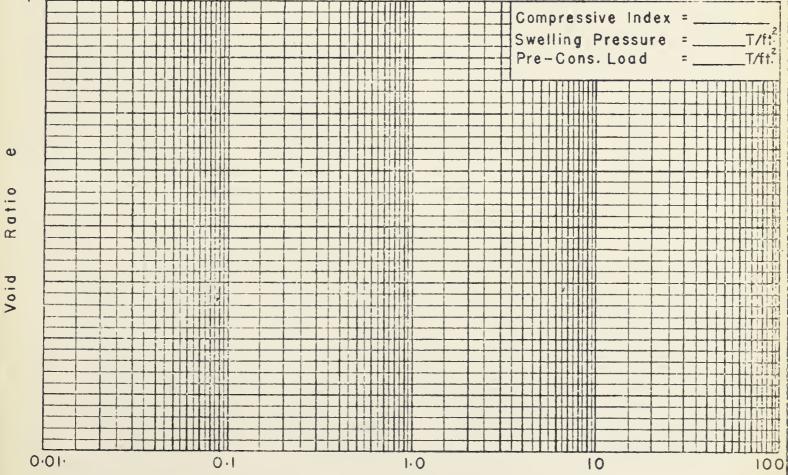HOLE   U of A   DEPTH 71'
TECHNICIAN   DATE 16 Jun 60

Specific Gravity of Soil Solids G_s = ___2·80___ Height of Soil Solids H_s = ___0·4280___ ins.

Void Ratio e (End) = _____ 1·410

Void Ratio e(Start) = _____ 1·080

Void Ratio e (Start Dimensions) = _____ 1·053

$e(End) = W\%(End) \times G_s$ $H_s = \left(\dfrac{Wt \cdot Soil}{G_s \times Area \times 2\cdot54}\right) ins.$ $e = previous\ e \pm \dfrac{Def'l.}{H_s}$

Time Interval	Load on Pan (gms)	Corr· Dial Reading (ins.)	Deflection (ins.)	Deflection H_s	Void Ratio e	Pressure $Kg/cm^2 = T/ft^2$
Continued	from previous page					
2 days	50	·6539	- 0063	-·015	1·439	·159
3 days	100	·6399	-·0140	-·033	1·406	325
··	200	·6160	-·0239	-·056	1·350	·598
2 days	400	5878	-·0282	-·066	1·284	1·18
··	800	·5509	-·0369	-·086	1·198	2·35
··	1600	·5079	-·0430	-·100	1·098	4·69
··	400	·5463	+·0384	+·090	1·188	1·18
5 days	100	·5977	+·0514	+·120	1·308	·325
7 days	20	·6412	+·0435	+·102	1·410	·0708
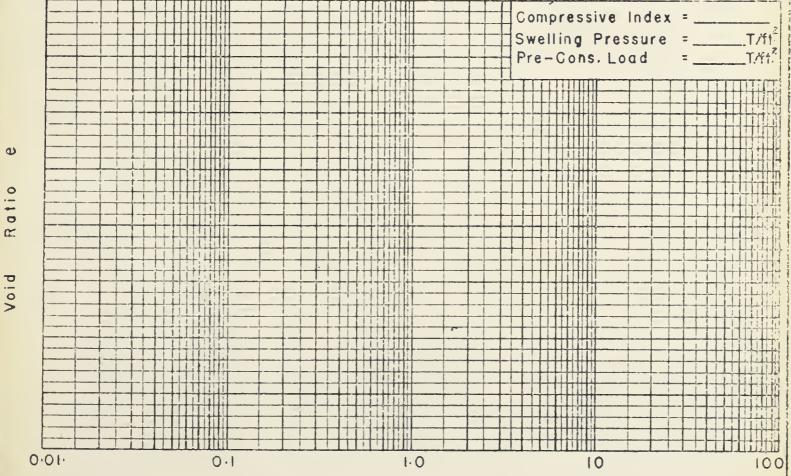
Compressive Index = ___0·31___
Swelling Pressure = ___4.7___ T/ft^2
Pre-Cons. Load   = _____ T/ft^2

Pressure $Kg./cm^2 (Tons/ft^2)$

--- Dashed portion of the curve is consolidation-rebound in the presence of MgO.

Plate 41

UNIVERSITY of ALBERTA
DEPT· of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
CONSOLIDATION RESULTS

PROJECT	Thesis
SITE	Dunvegan
SAMPLE	Undisturbed (Rebound with KOH)
LOCATION	
HOLE	U of A	DEPTH 73'
TECHNICIAN	PAT	DATE 15 Jun 60

Specific Gravity of Soil Solids G_s = __2·80__ Height of Soil Solids H_s = __0·4677__ ins.

Void Ratio e (End) = _____ 1·204

Void Ratio e(Start) = _____ 0·949

Void'Ratio e (Start Dimensions) = _____ 0·907

e(End) = W%(End) x G_s $H_s = \left(\dfrac{Wt \cdot Soil}{G_s \times Area \times 2·54}\right)$ ins.   e = previous e ± $\dfrac{Def'l.}{H_s}$

Time Interval	Load on Pan (gms)	Corr. Dial Reading (ins.)	Deflection (ins.)	$\dfrac{Deflection}{H_s}$	Void Ratio e	Pressure Kg/cm^2= T/ft^2
	0	·4640			0·949	
11 days	40	·6053	+·1413	+·302	1·251	·0702
1 day	200	·5964	−·0089	−·019	1·252	·304
2 days	400	·5730	−·0234	−·050	1·182	·597
2 days	800	·5454	−·0276	−·059	1·123	1·18
1 day	1600	5133	−·0321	−·069	1·054	2·35
2 days	400	·5423	+·0290	+·062	1·116	·597
"	100	5829	+·0406	+·087	1·203	·147
1 day	200	·5773	−·0056	−·012	1·191	·304
2 days	400	·5617	−·0156	−·033	1·158	·597
5 days	800	·5368	−·0249	−·053	1·105	1·18
3 days	1600	·5110	−·0258	−·055	1·050	2·35
2 days	*400	·5392	+·0282	+·060	1·110	·597
9 days	100	·5790	+·0398	+·085	1·195	·147

Compressive Index = _____

Swelling Pressure = _____ T/ft^2

Pre-Cons. Load = _____ T/ft^2

Void Ratio e

Pressure Kg./cm^2 (Tons/ft^2)
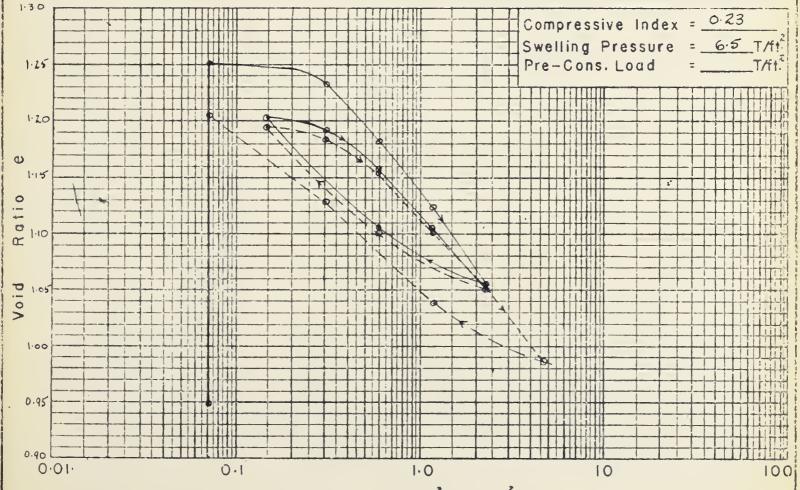
* Allowed to rebound with KOH in the place of water.

Plate 42

UNIVERSITY of ALBERTA
DEPT. of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
CONSOLIDATION RESULTS

PROJECT	Thesis
SITE	Dunvegan
SAMPLE	Undisturbed (Rebound with KOH)
LOCATION	
HOLE U of A	DEPTH 73'
TECHNICIAN PAT	DATE 15 Jun 60

Specific Gravity of Soil Solids G_s = _____ Height of Soil Solids H_s = _____ ins.

Void Ratio e (End) = _____

Void Ratio e (Start) = _____

Void Ratio e (Start Dimensions) = _____

$$e(End) = W\%(End) \times G_s \qquad H_s = \left(\frac{Wt \cdot Soil}{G_s \times Area \times 2.54}\right) ins. \qquad e = previous\ e \pm \frac{Def'l.}{H_s}$$

Time Interval	Load on Pan (gms)	Corr. Dial Reading (ins.)	Deflection (ins.)	Deflection H_s	Void Ratio e	Pressure Kg/cm² = T/ft²
Continued	From previous page					
2 days	200	.5738	−.0052	−.011	1.184	.304
3 days	400	.5600	−.0138	−.030	1.154	.597
2 days	800	.5396	−.0204	−.044	1.110	1.18
"	1600	.5123	−.0273	−.058	1.052	2.35
1 day	3200	.4812	−.0311	−.066	0.986	4.69
"	800	.5055	+.0243	+.052	1.038	1.18
4 days	200	.5479	+.0424	+.091	1.129	.304
7 days	40	.5828	+.0349	+.075	1.204	.0702

Compressive Index = 0.23

Swelling Pressure = 6.5 T/ft²

Pre-Cons. Load = ____ T/ft²

Pressure Kg./cm² (Tons/ft.²)

- - - Dashed portion of the curve is consolidation-rebound in the presence of KOH

Plate 43

UNIVERSITY of ALBERTA
DEPT· of CIVIL ENGINEERING
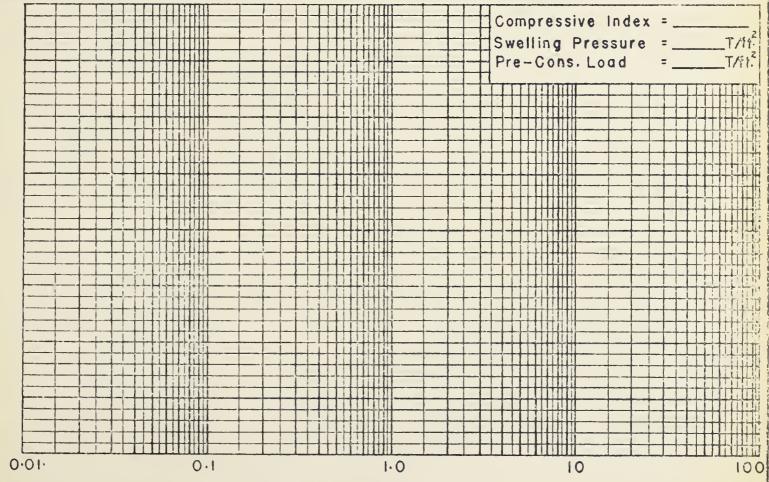## SOIL MECHANICS LABORATORY
CONSOLIDATION RESULTS

PROJECT Thesis
SITE Dunvegan
SAMPLE Undisturbed (Rebound with Ca(OH)₂)
LOCATION
HOLE UofA   DEPTH 76'
TECHNICIAN PAT   DATE 15 Jun 60

Specific Gravity of Soil Solids G_S = _2·80_ Height of Soil Solids H_S = _·4897_ ins.

Void Ratio e (End) = _____ 1·061

Void Ratio e(Start) = _____ 0·857

Void Ratio e (Start Dimensions) = _____ 0·794

$e(End) = W\%(End) \times G_S$ $H_S = \left(\frac{Wt \cdot Soil}{G_S \times Area \times 2·54}\right) ins.$ $e = previous\ e \pm \frac{Def'l.}{H_S}$

Time Interval	Load on Pan (gms)	Corr. Dial Reading (ins.)	Deflection (ins.)	$\frac{Deflection}{H_S}$	Void Ratio e	Pressure Kg/cm² = T/ft²
	0	·6300			0·857	
12 days	20	·6250	+·0950	+·194	1·051	·0704
2 days	200	·6062	−·0188	−·038	1·013	·597
"	400	·5856	−·0206	−·042	0·971	1·18
1 day	800	·5596	−·0260	−·053	0·918	2·35
"	400	·5688	+·0092	−·019	0·937	1·18
2 days	100	·6032	+·0344	+·070	1·007	·304
4 days	20	·6420	+·0388	+·079	1·086	·0704
5 days	50	·6359	−·0061	−·012	1·074	·147
2 days	100	·6272	−·0087	−·018	1·056	·304
"	200	·6090	−·0182	−·037	1·019	·597
"	400	·5868	−·0222	−·045	0·974	1·18
1 day	800	·5613	−·0255	−·052	0·922	2·35
"	*400	·5702	+·0089	+·018	0·940	1·18

Compressive Index = _____

Swelling Pressure = _____ T/ft²

Pre-Cons. Load = _____ T/ft²

Void Ratio e

Pressure Kg./cm² (Tons/ft²)

0·01   0·1   1·0   10   100

* Allowed to rebound with Ca(OH)² in the place of water.

Plate 44

UNIVERSITY of ALBERTA
DEPT· of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
CONSOLIDATION RESULTS

PROJECT	Thesis		
SITE	Dunvegan		
SAMPLE	Undisturbed (Rebound with Ca(OH)²)		
LOCATION			
HOLE	U of A	DEPTH	76'
TECHNICIAN	PAT	DATE	15 Jun 60

Specific Gravity of Soil Solids G_S = _____ Height of Soil Solids H_S = _____ ins.
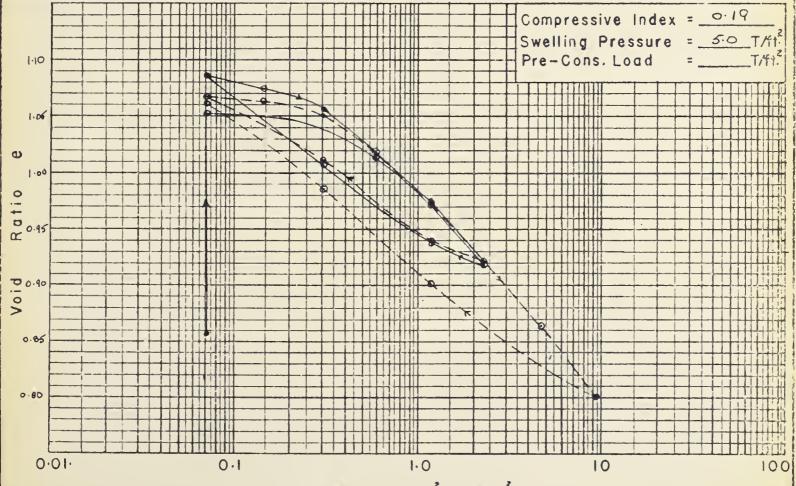
Void Ratio e (End) = _____

Void Ratio e(Start) = _____

Void Ratio e (Start Dimensions) = _____

$$e(End) = W\%(End) \times G_S \qquad H_S = \left(\frac{Wt \cdot Soil}{G_S \times Area \times 2.54}\right) ins. \qquad e = previous\ e \pm \frac{Def'l.}{H_S}$$

Time Interval	Load on Pan (gms)	Corr. Dial Reading (ins.)	Deflection (ins.)	Deflection H_S	Void Ratio e	Pressure Kg/cm² = T/ft²
Continued from previous page						
5 days	100	.6052	+.0350	+.071	1.011	.304
4 days	20	.6333	+.0281	+.057	1.068	.0704
1 day	50	.6307	−.0026	−.005	1.063	.147
"	100	.6243	−.0064	−.013	1.050	.304
2 days	200	.6087	−.0166	−.032	1.018	.597
-	400	.5867	−.0220	−.045	0.973	1.18
1 day	800	.5623	−.0244	−.050	0.923	2.35
"	1600	.5332	−.0291	−.059	0.864	4.69
"	3200	.5019	−.0313	−.064	0.800	9.37
2 days	400	.5574	+.0495	+.101	0.901	1.18
4 days	100	.5932	+.0418	+.085	0.986	.304
5 days	20	.6299	+.0367	+.075	1.061.	.0704

Compressive Index = 0.19
Swelling Pressure = 5.0 T/ft²
Pre-Cons. Load = _____ T/ft²

--- Dashed portion of the curve is consolidation − rebound in the presence of Ca(OH)²